

Physics of the Large Hadron Collider

Chris Quigg

Fermilab

Why Hadron Colliders?

Discovery machines

W^\pm, Z^0, t, H, \dots

Precision instruments

M_W, m_t, B_s oscillation frequency, ...

Large energy reach · High event rate

Why Hadron Colliders?

Explore a rich diversity of elementary processes
at the highest accessible energies:

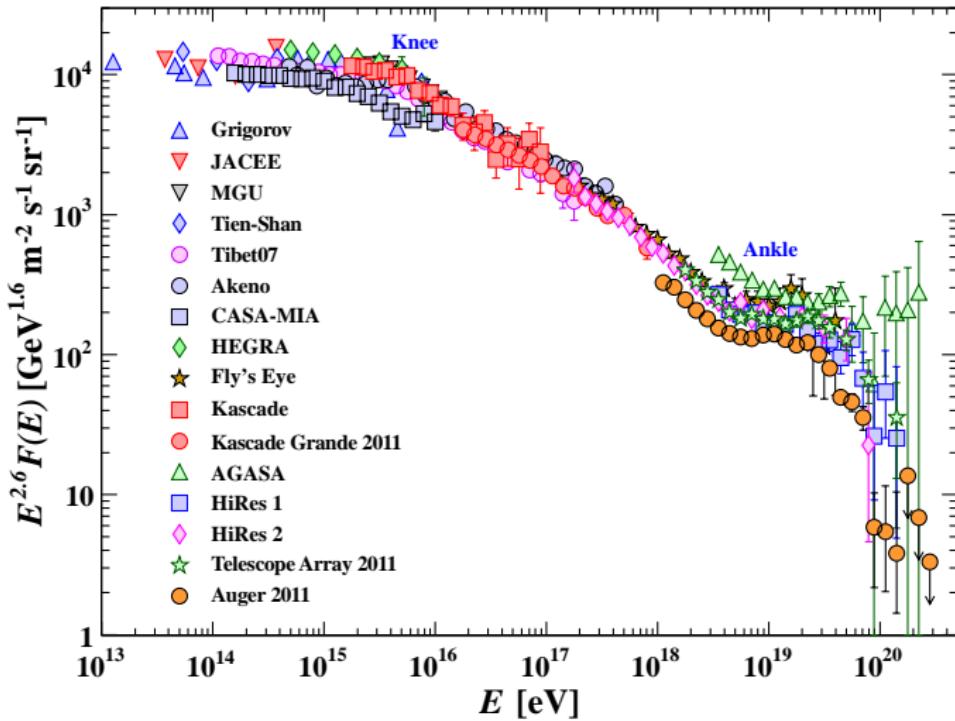
$$(q_i, \bar{q}_i, g, \dots) \otimes (q_i, \bar{q}_i, g, \dots)$$

Example: quark-quark collisions at $\sqrt{s} = 1$ TeV

If 3 quarks share half the proton's momentum ($\langle x \rangle = \frac{1}{6}$),
require pp collisions at $\sqrt{s} = 6$ TeV

↪ Fixed-target machine with beam momentum
 $p \approx 2 \times 10^4$ TeV = 2×10^{16} eV (cf. cosmic rays).

Cosmic-ray Spectrum



$$\frac{dI}{dE}(2 \times 10^{16} \text{ eV}) = (3 - 5) \times 10^{-16} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ eV}^{-1}$$

How to achieve?

Fixed-target, $p \approx 2 \times 10^4$ TeV

Ring radius is

$$r = \frac{10}{3} \cdot \left(\frac{p}{1 \text{ TeV}} \right) / \left(\frac{B}{1 \text{ tesla}} \right) \text{ km.}$$

Conventional copper magnets ($B = 2$ teslas) \leadsto

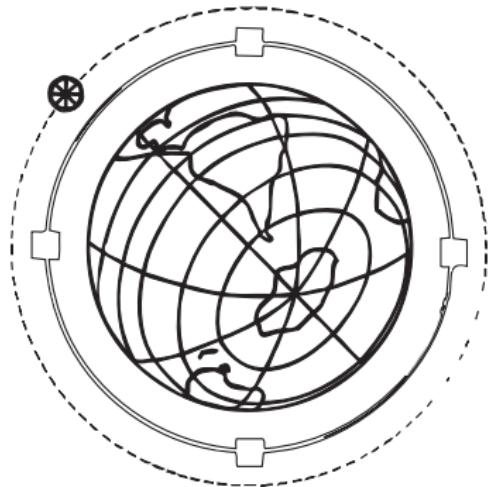
$$r \approx \frac{1}{3} \times 10^5 \text{ km.}$$

$\approx \frac{1}{12}$ size of Moon's orbit

10-tesla field reduces the accelerator to mere Earth size
($R_{\oplus} = 6.4 \times 10^3$ km).

Fermi's Dream Machine (1954)

5000-TeV protons to reach $\sqrt{s} \approx 3$ TeV
2-tesla magnets at radius 8000 km



Projected operation 1994, cost \$170 billion
(inflation assumptions not preserved)

Key Advances in Accelerator Technology

- Alternating-gradient (“strong”) focusing, invented by Christofilos, Courant, Livingston, and Snyder.

Before and After . . .

Synchrotron	Beam Tube	Magnet Size
Bevatron (6.2 GeV)	1 ft \times 4 ft	9 $\frac{1}{2}$ ft \times 20 $\frac{1}{2}$ ft
FNAL Main Ring (400 GeV)	\sim 2 in \times 4 in	14 in \times 25 in
LHC (\rightarrow 7 TeV)	56 mm	(SC)

- The idea of colliding beams.
- Superconducting accelerator magnets based on “type-II” superconductors, including NbTi and Nb₃Sn.

Key Advances . . .

- Active optics to achieve real-time corrections of the orbits makes possible reliable, highly tuned accelerators using small-aperture magnets. Also “cooling,” or phase-space compaction of stored antiprotons.
- The evolution of vacuum technology. Beams stored for approximately 20 hours travel $\sim 2 \times 10^{10}$ km, about 150 times the Earth–Sun distance, without encountering a stray air molecule.
- The development of large-scale cryogenic technology, to maintain many km of magnets at a few kelvins.

Hadron Colliders through the Ages

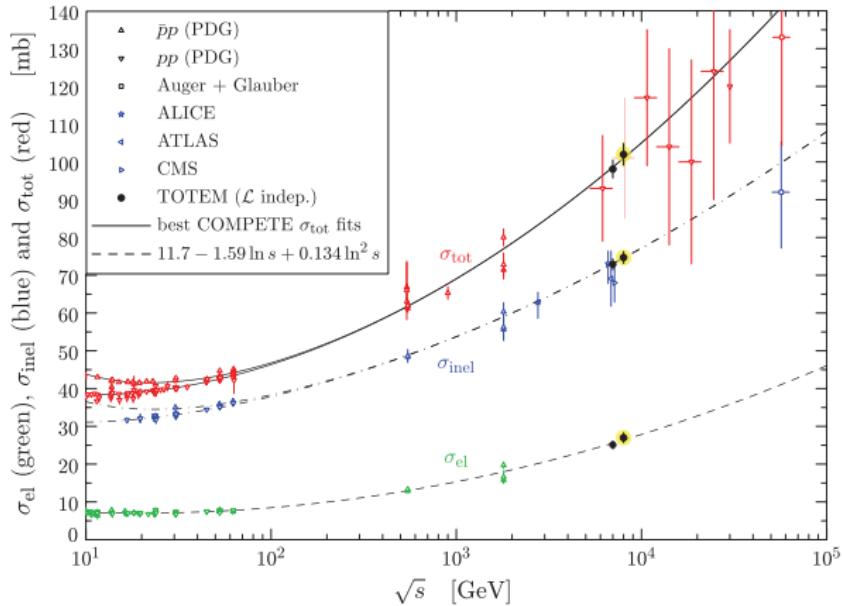
- CERN Intersecting Storage Rings: pp collider at $\sqrt{s} \rightarrow 63$ GeV. Two rings of conventional magnets.
- $S\bar{p}S$ Collider at CERN: $\bar{p}p$ collisions at $\sqrt{s} = 630(\rightarrow 900)$ GeV in conventional-magnet SPS.
- Fermilab Tevatron Collider: $\bar{p}p$ collisions at $\sqrt{s} \approx 2$ TeV with 4-T SC magnets in a 2π -km tunnel.
- Brookhaven Relativistic Heavy-Ion Collider: 3.45-T dipoles in 3.8-km tunnel. Polarized pp , $\sqrt{s} \rightarrow 0.5$ TeV
- Large Hadron Collider at CERN: 14-TeV pp collider in the 27-km LEP tunnel, using 9-T magnets at 1.8 K.

High-energy collider parameters, 2012 *Review of Particle Properties* §28

Large Hadron Collider at CERN

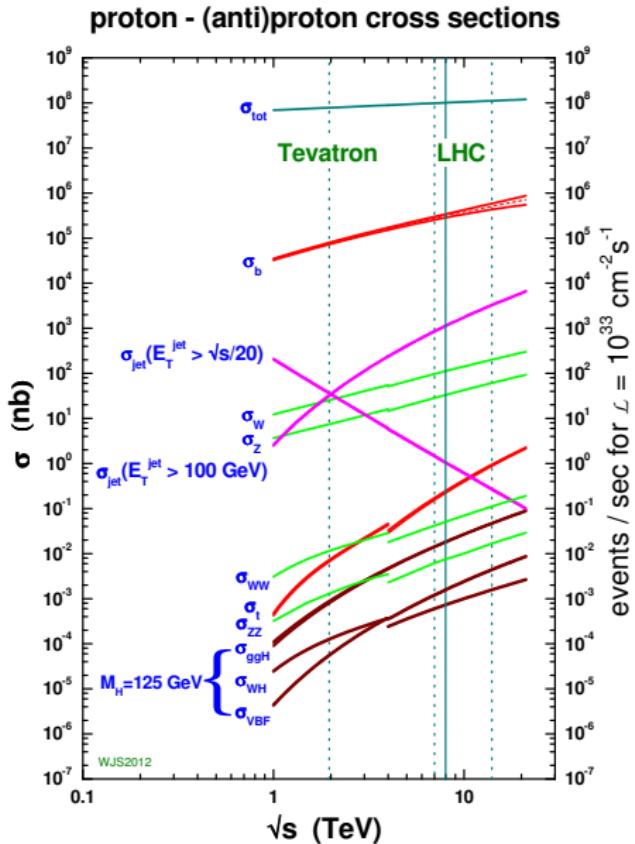


$\sqrt{s} = 8$ TeV Interaction Rates

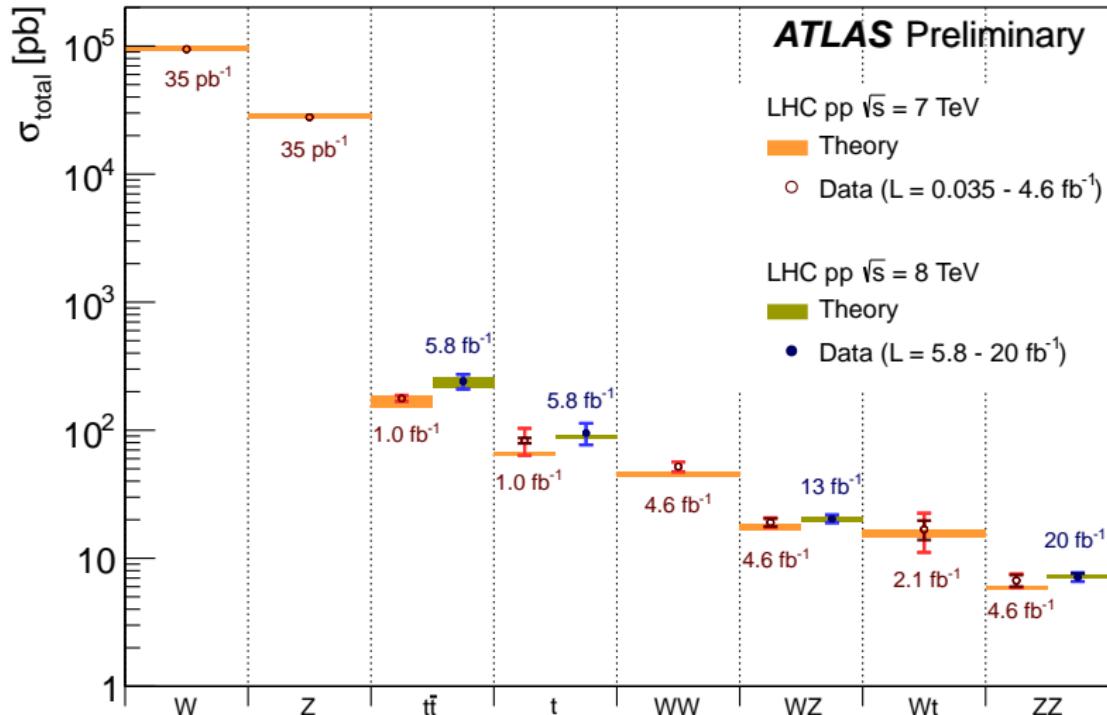


$$\begin{aligned}\sigma_{\text{tot}} & (101.7 \pm 2.9) \text{ mb} \\ \sigma_{\text{inel}} & (74.7 \pm 1.7) \text{ mb} \\ \sigma_{\text{el}} & (27.1 \pm 1.4) \text{ mb}\end{aligned}$$

Collider Cross Sections



Standard-model Cross Sections



$$\sigma_{\text{tot}} \approx 10^{11} \text{ pb}$$

Luminosity

Number N of events of interest

$$N = \sigma \int dt \mathcal{L}(t)$$

$\mathcal{L}(t)$: instantaneous luminosity [in $\text{cm}^{-2} \text{ s}^{-1}$]

Bunches of n_1 and n_2 particles collide head-on at frequency f :

$$\mathcal{L}(t) = f \frac{n_1 n_2}{4\pi \sigma_x \sigma_y}$$

$\sigma_{x,y}$: Gaussian rms \perp beam sizes

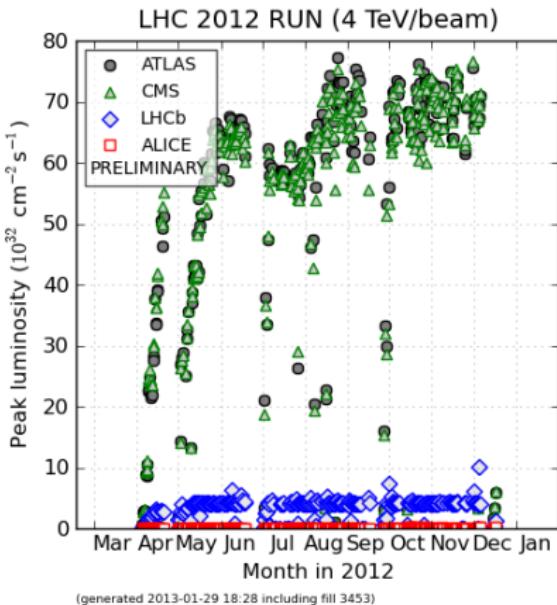
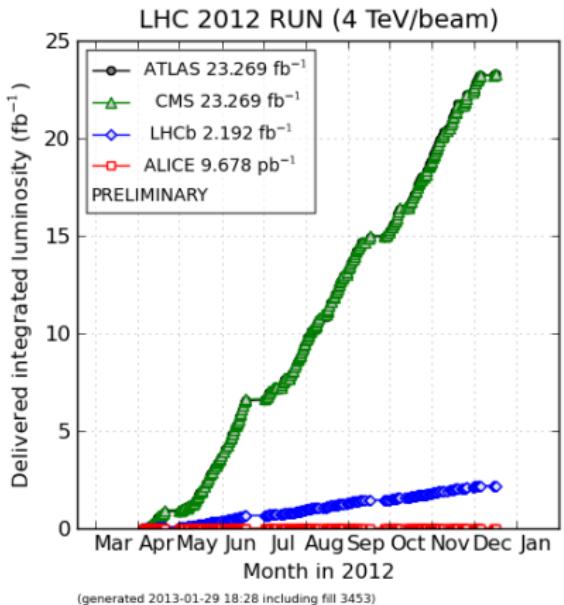
Edwards & Syphers, 2012 *Review of Particle Physics*, §27

LHC lumi calculator Zimmerman, "LHC: The Machine," SSI 2012

Exercise 1

- (a) Estimate the integrated luminosity required to make a convincing observation of each of the standard-model final states shown in the ATLAS plot [above](#). Take into account the gauge-boson branching fractions given in the 2012 *Review of Particle Physics*.
- (b) Taking a nominal year of operation as 10^7 s, translate your results into the required average luminosity.

LHC Luminosity, 2012



$$\mathcal{L}_{\text{peak}} \approx 7.7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \text{ ATLAS \& CMS}$$

Collider kinematics

Because of its properties under Lorentz boosts, rapidity,

$$y \equiv \frac{1}{2} \ln \left| \frac{E + p_z}{E - p_z} \right|,$$

is a highly convenient longitudinal variable for an individual particle or a jet. *Pseudorapidity*,

$$\eta \equiv -\ln \tan(\theta^*/2),$$

is a close approximation to y in the setting of collider detectors, and can be measured, even when the mass of the outgoing object is unknown.

Exercise 2

(a) Expand the definition

$$y \equiv \frac{1}{2} \ln \left| \frac{E + p_z}{E - p_z} \right|$$

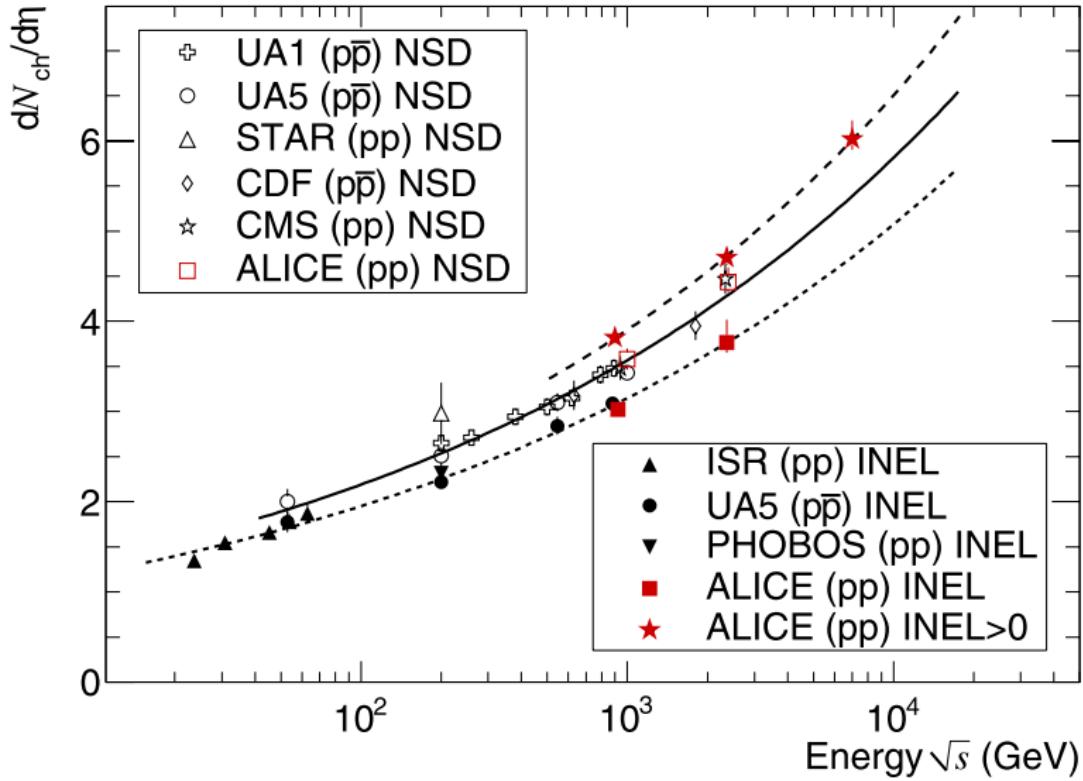
of rapidity for an object with mass m , under the assumption that $p \gg m$, to show that as $m/p \rightarrow 0$,

$$y \rightarrow \eta \equiv -\ln \tan(\theta^*/2).$$

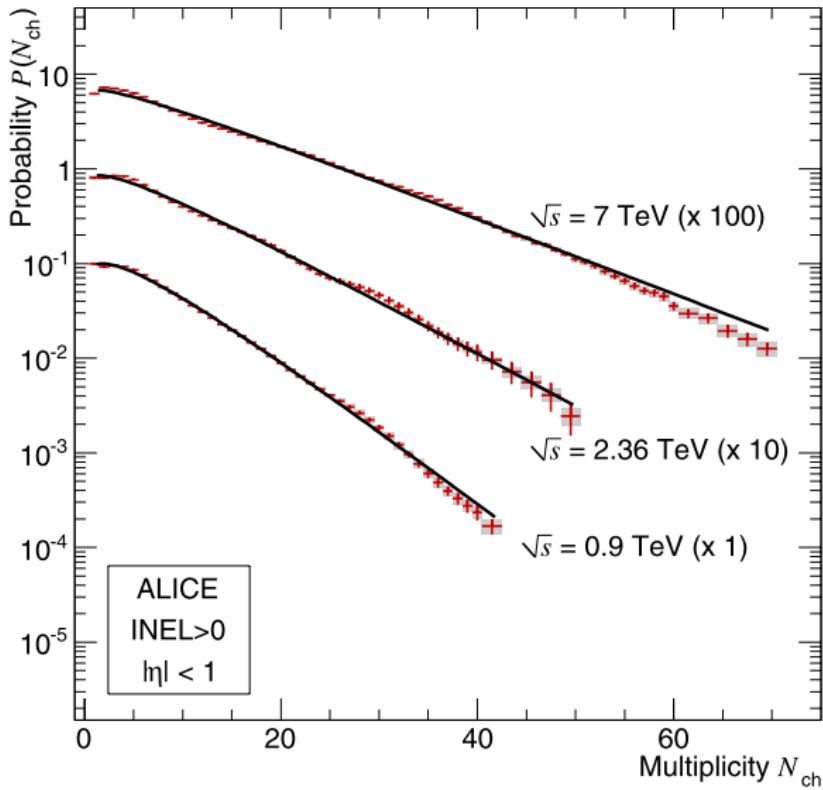
cf. 2012 Review of Particle Physics §43.5.2

(b) For pion production, compute the maximum c.m. rapidity at $\sqrt{s} = (8, 14)$ TeV and deduce the angular coverage required to observe the full range.

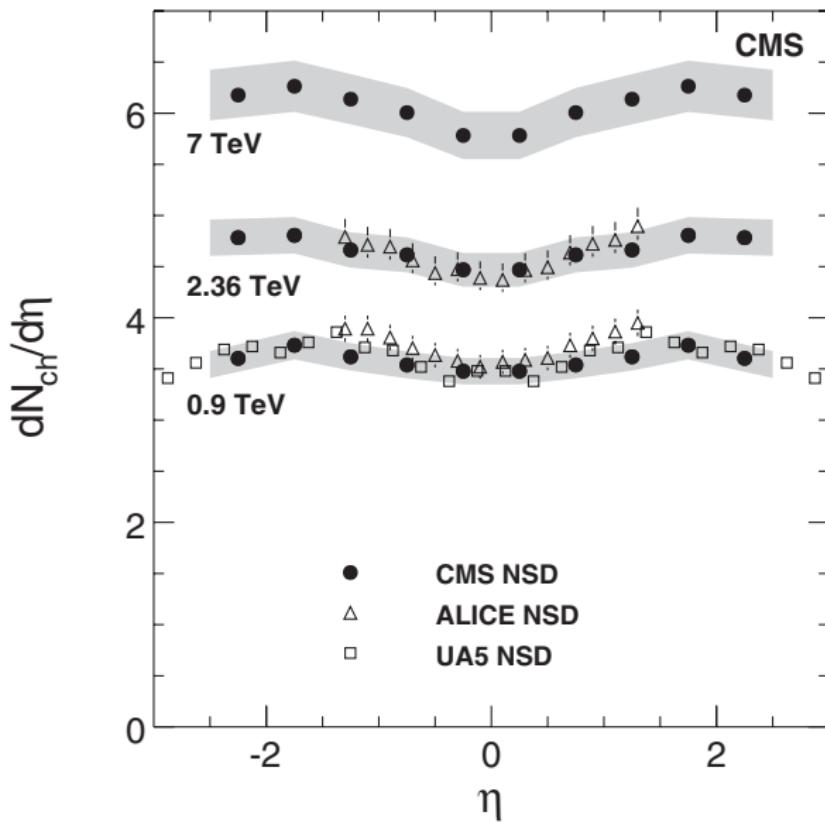
Charged-particle density, $\eta \approx 0$



Charged-particle multiplicity, $|\eta| < 1$

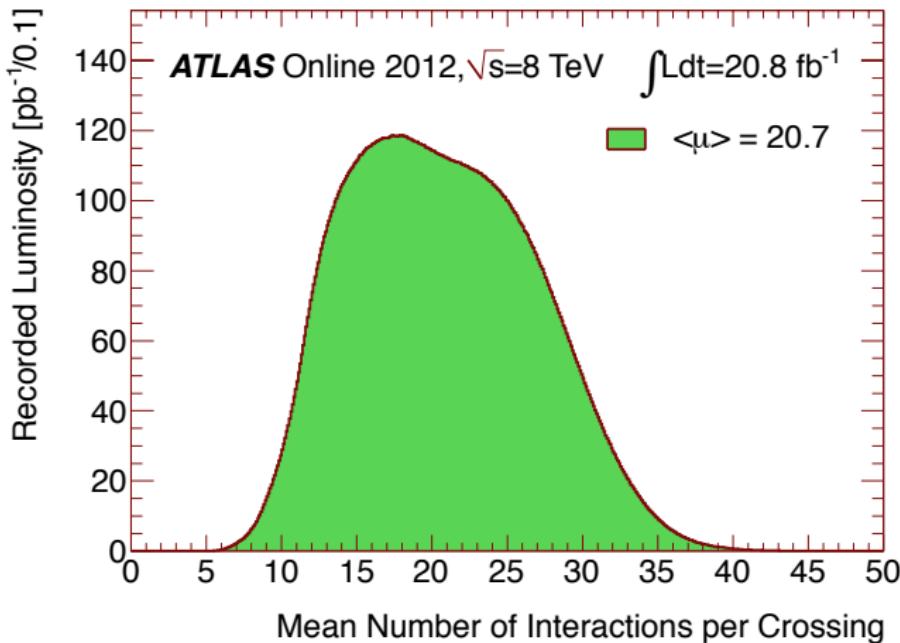


Charged-particle spectra

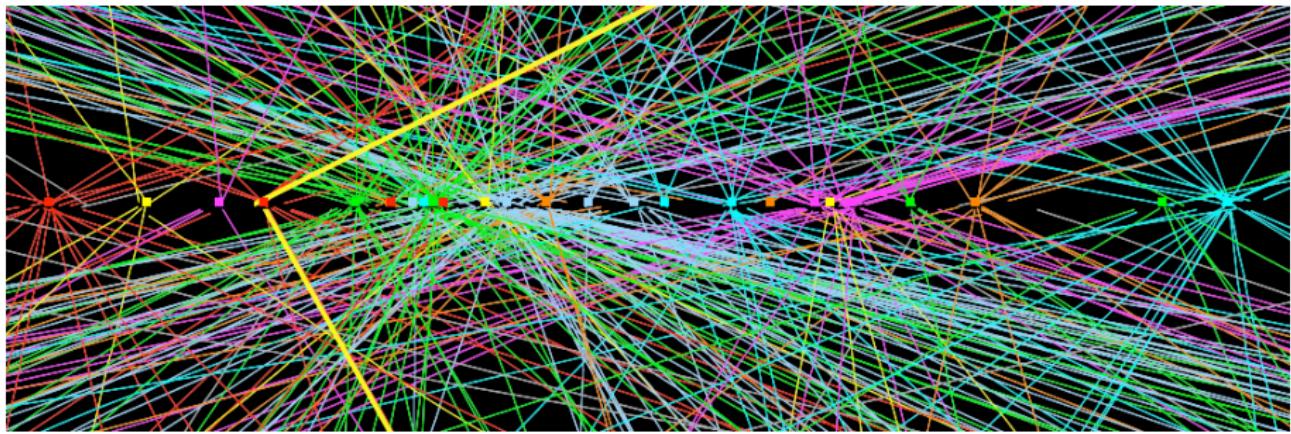


Pileup

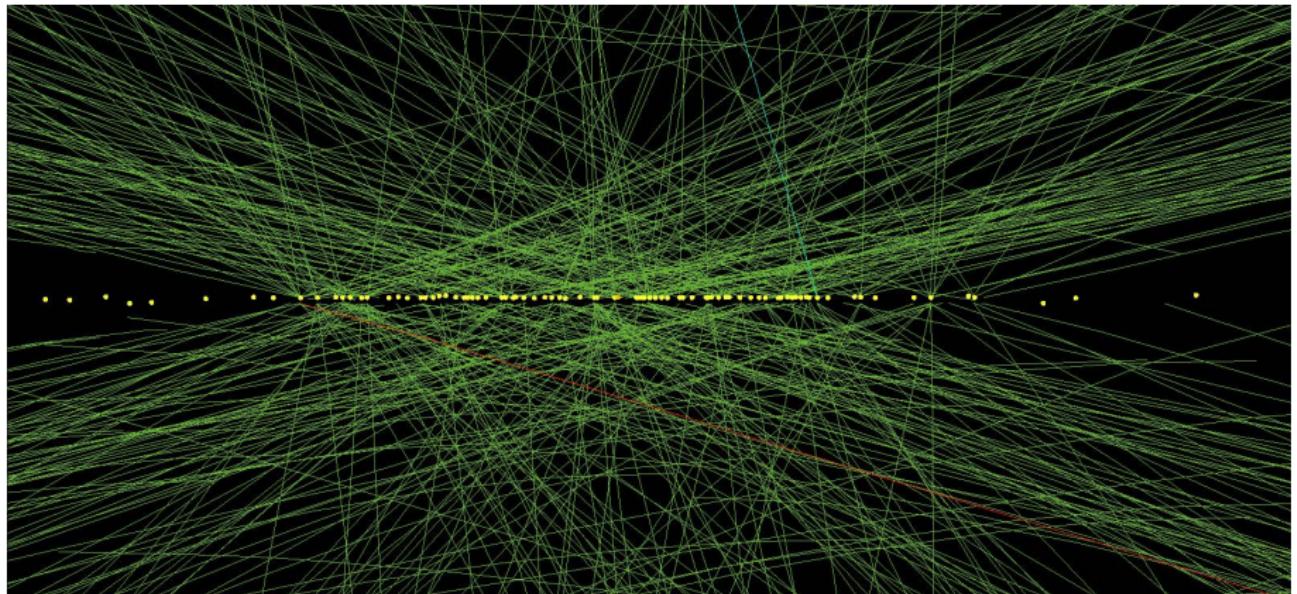
Typical LHC operation: 1.5×10^{11} protons / bunch
bunch separation 50 ns
 \leadsto multiple interactions / crossing



Pileup: $Z \rightarrow \mu^+ \mu^-$ in 25 interactions in ATLAS



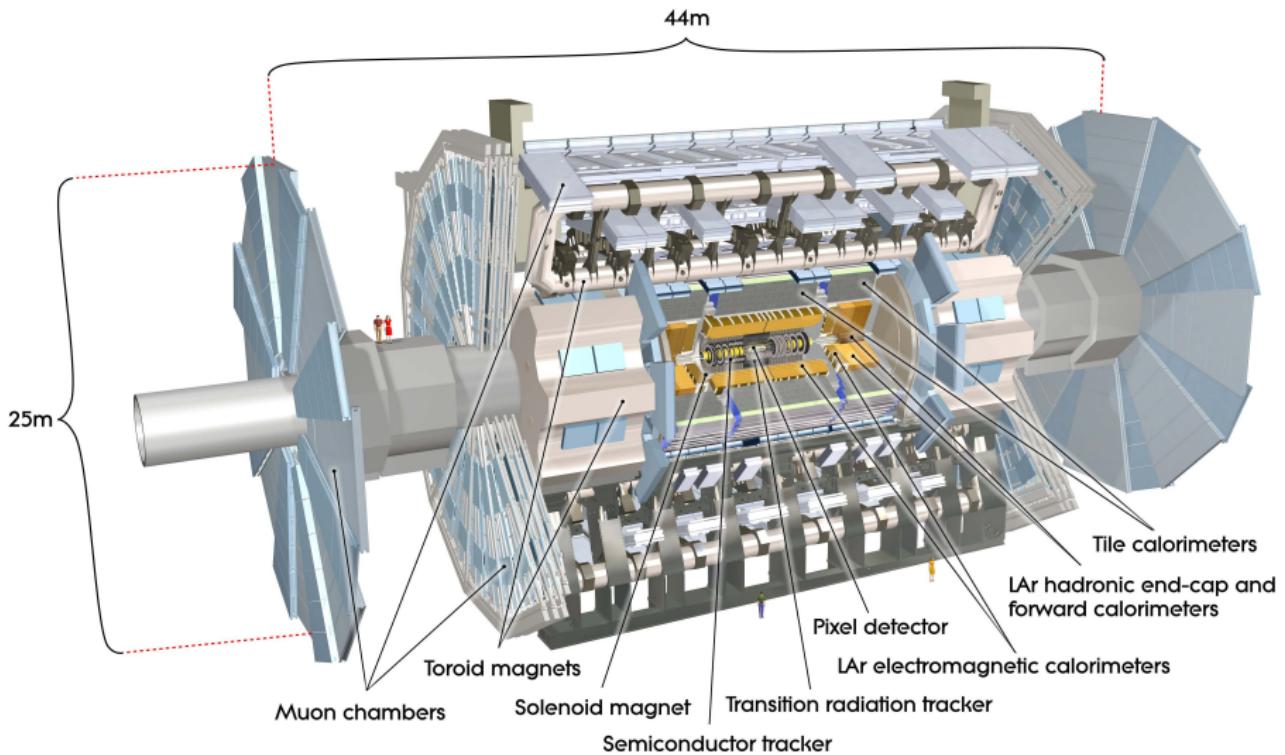
Pileup: 78 interactions in CMS



Exercise 3

Consider the reaction $p^\pm p \rightarrow \text{jet}_1 + \text{jet}_2 + \text{anything}$ at c.m. energy \sqrt{s} . Denote the rapidity of the dijet system as $y_{\text{boost}} \equiv \frac{1}{2}(y_1 + y_2)$ and the individual jet rapidity in the dijet rest frame as $y^* \equiv \frac{1}{2}(y_1 - y_2)$.

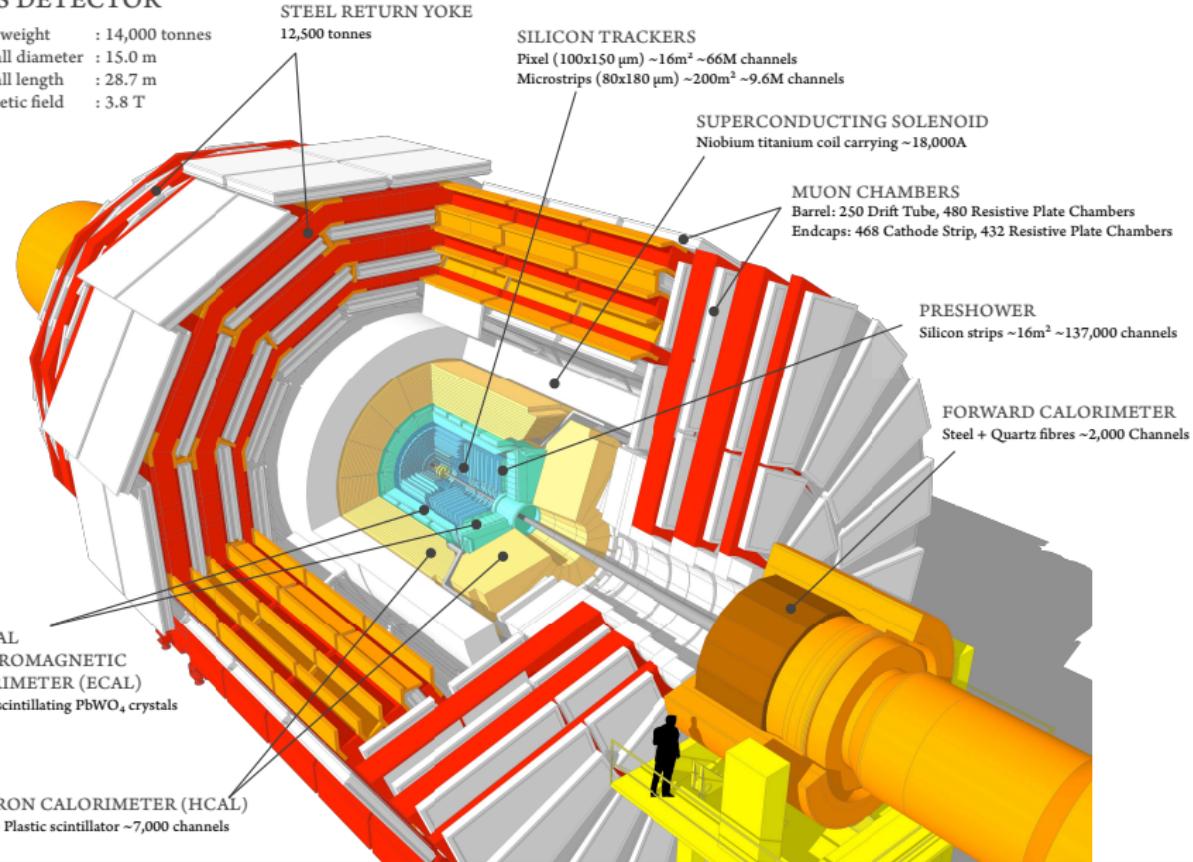
- Neglecting the invariant masses of the individual jets with respect to p_\perp , show that the invariant mass of the dijet system, and thus of the colliding partons, is $\sqrt{\hat{s}} = 2p_\perp \cosh y^*$.
- Deduce the momentum fractions carried by the two colliding partons. Show that $x_{a,b} = \sqrt{\tau} e^{\pm y_{\text{boost}}}$, where $\tau \equiv \hat{s}/s$.



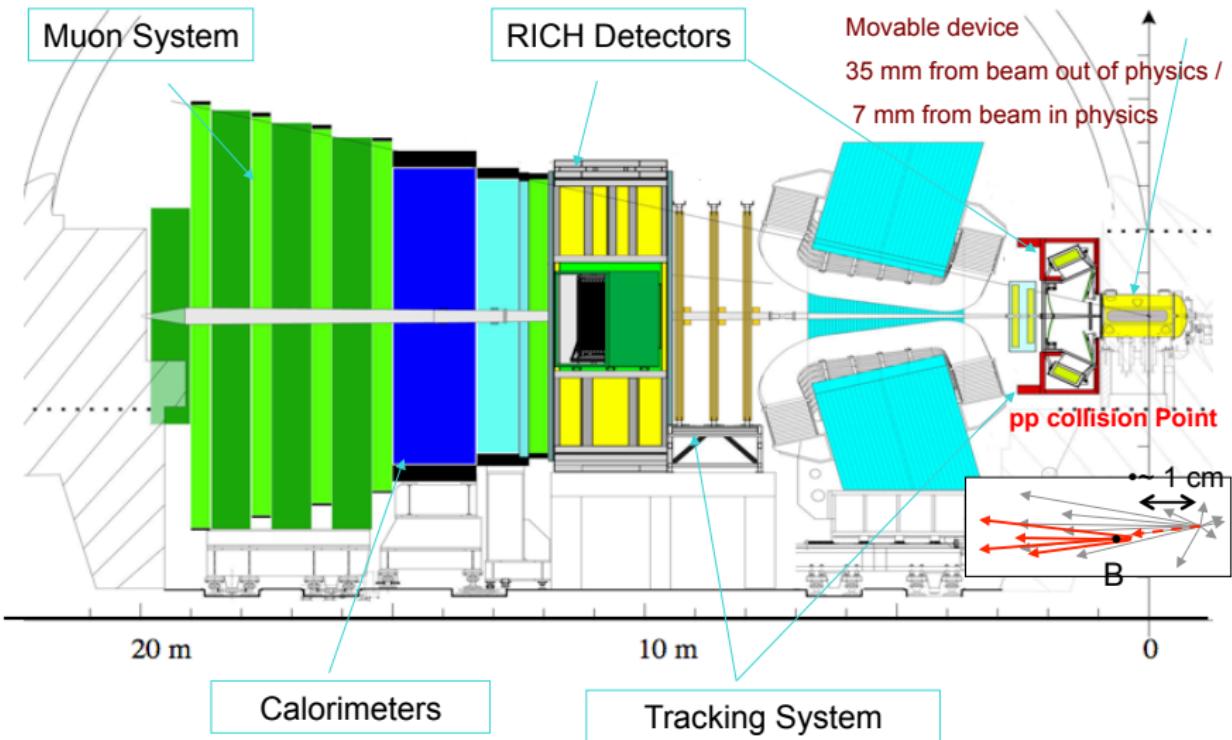
CMS (Compact Muon Solenoid)

CMS DETECTOR

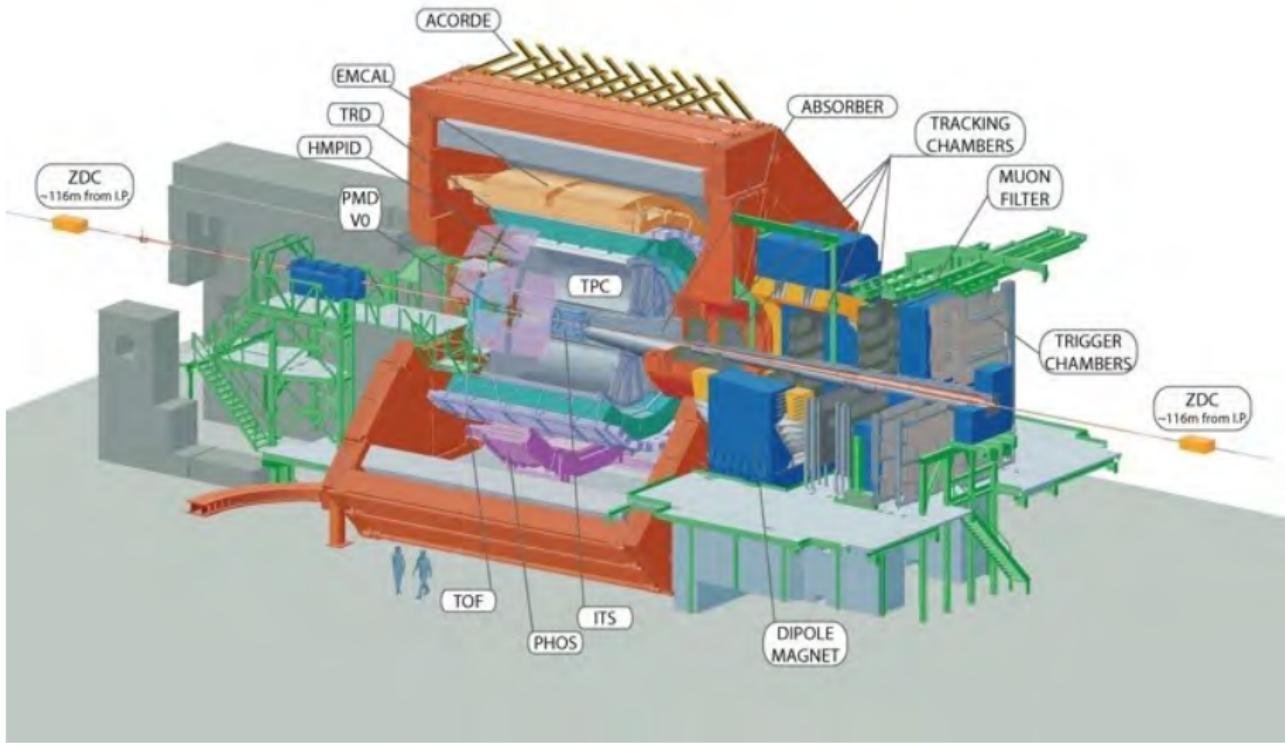
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



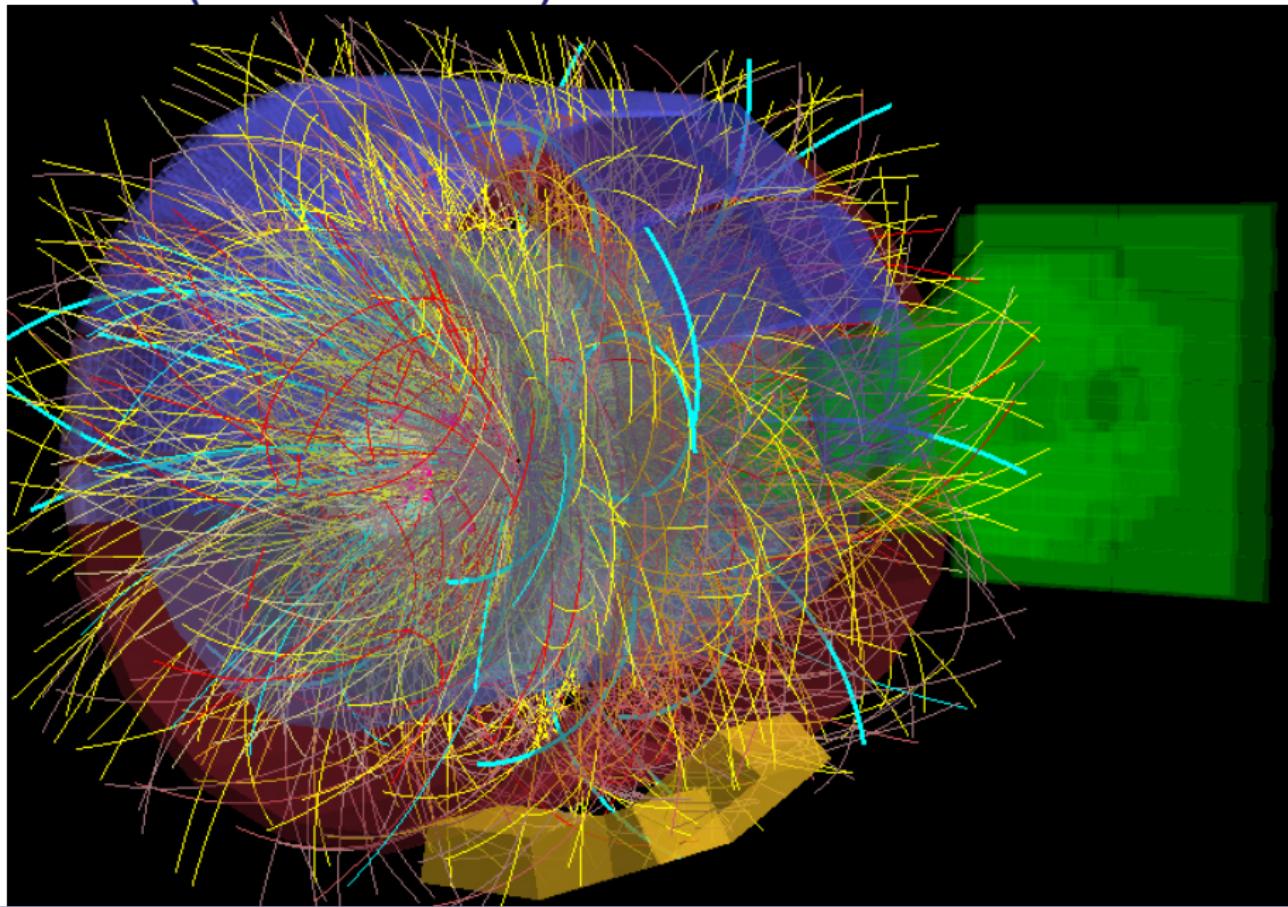
LHCb

Vertex Locator
VELO

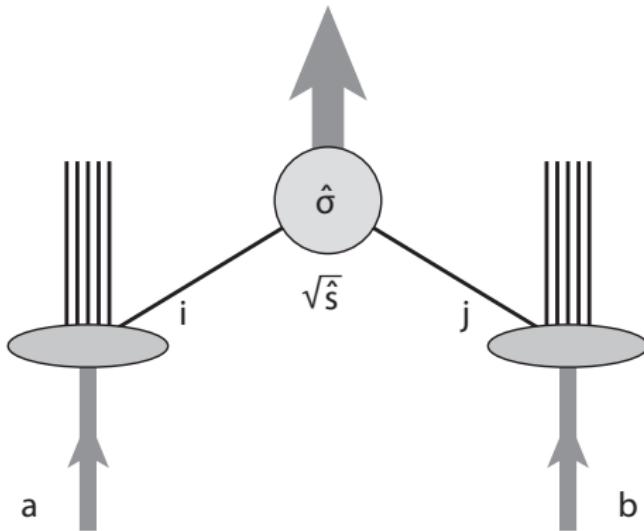
ALICE



ALICE (Pb–Pb event)



Computing Cross Sections: *factorization*



$$\frac{d\sigma}{dy_1 dy_2 dp_{\perp}} = \sum_{ij} \frac{2\pi p_{\perp}}{(1 + \delta_{ij})s} \left[f_i^{(a)}(x_a, \hat{s}) f_j^{(b)}(x_b, \hat{s}) \hat{\sigma}_{ij}(\hat{s}, \hat{t}, \hat{u}) + (i \leftrightarrow j) \right]$$

... + fragmentation (partons \rightarrow particles)

What Is a Proton?

(For hard scattering) a broad-band, unselected beam of quarks, antiquarks, gluons, & perhaps other constituents, characterized by parton densities

$$f_i^{(a)}(x_a, Q^2),$$

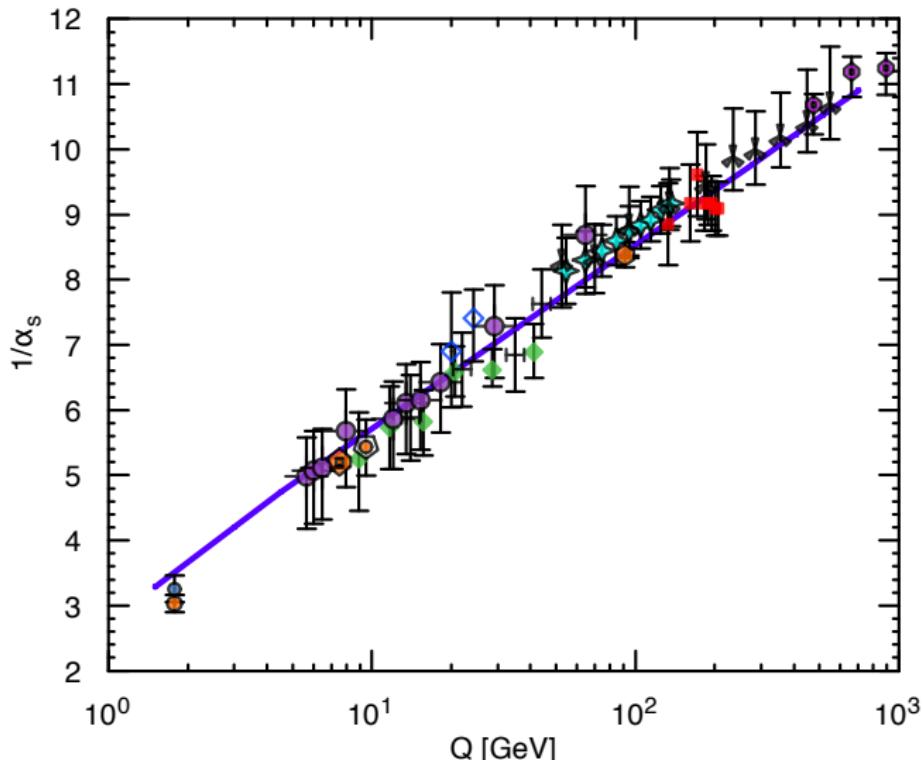
... number density of species i with momentum fraction x_a of hadron a seen by probe with resolving power Q^2 .

Q^2 evolution given by QCD perturbation theory

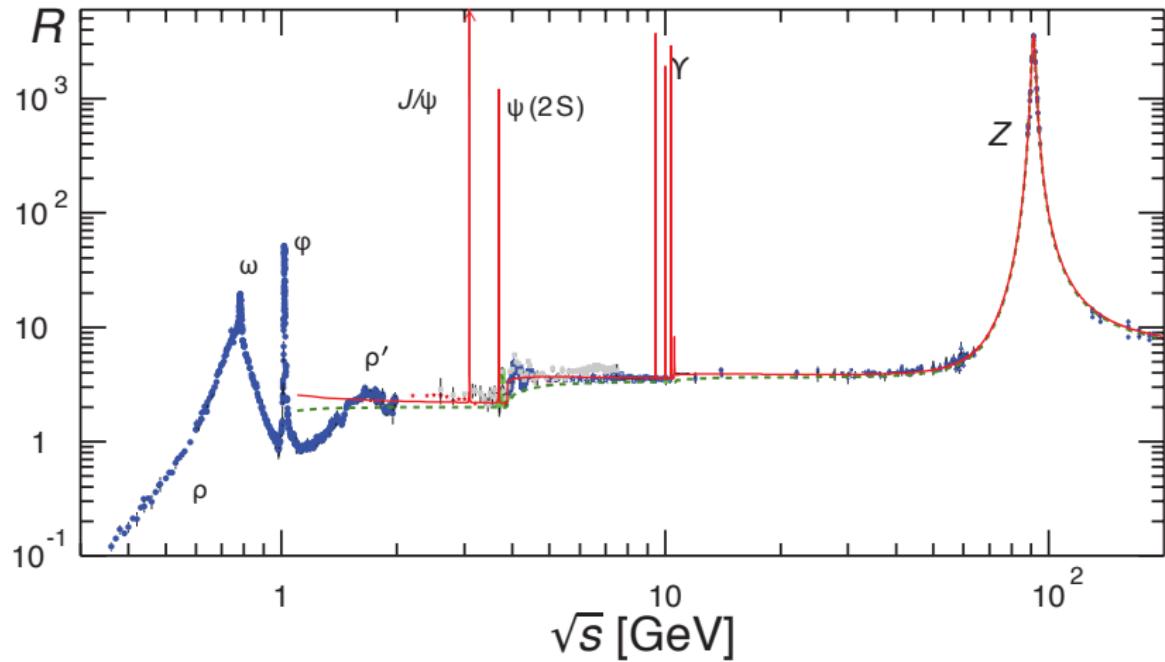
$$f_i^{(a)}(x_a, Q_0^2): \text{nonperturbative}$$

Asymptotic Freedom

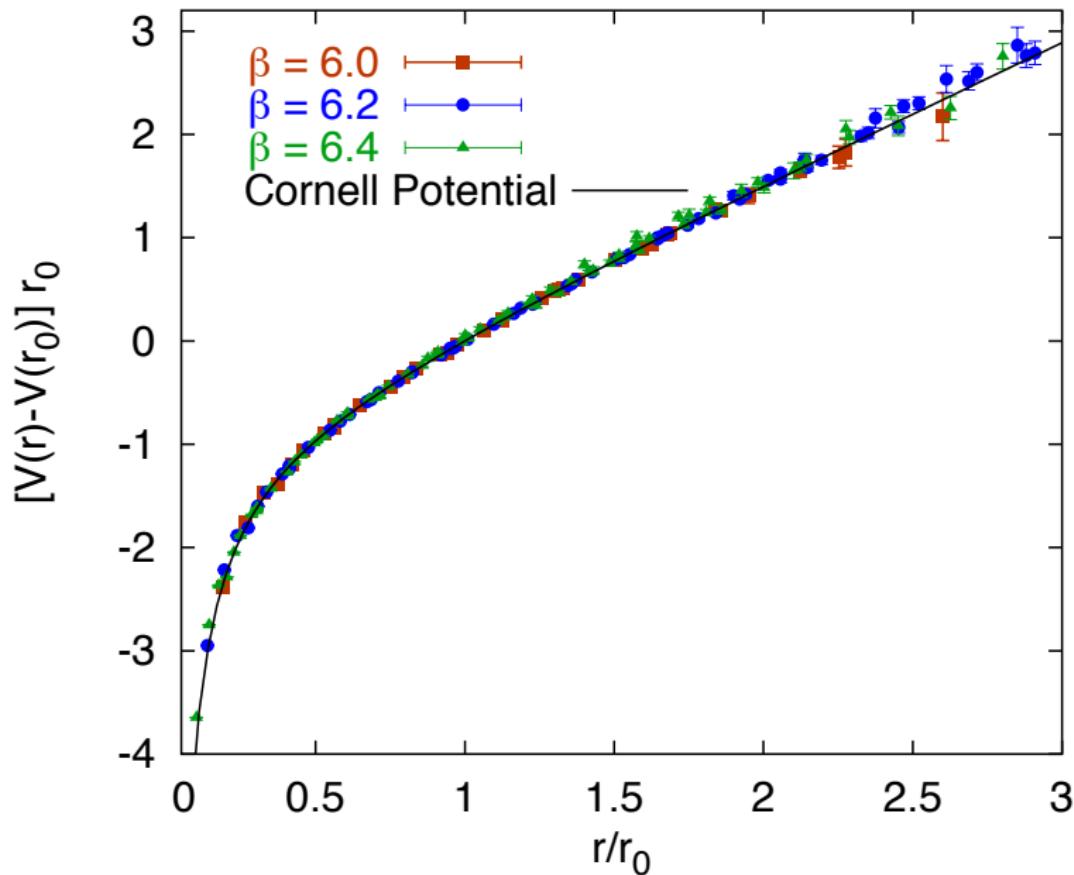
$$\frac{1}{\alpha_s(Q)} = \frac{1}{\alpha_s(\mu)} + \frac{(33 - 2n_f)}{6\pi} \ln \left(\frac{Q}{\mu} \right)$$



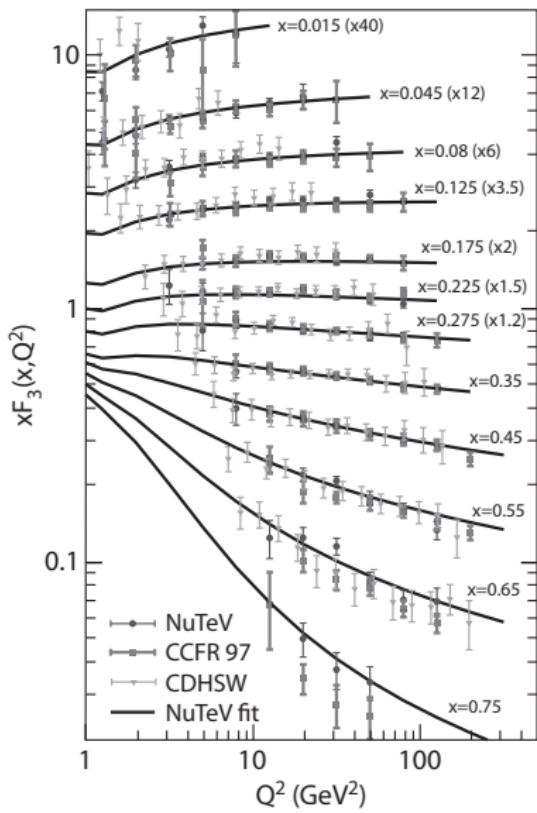
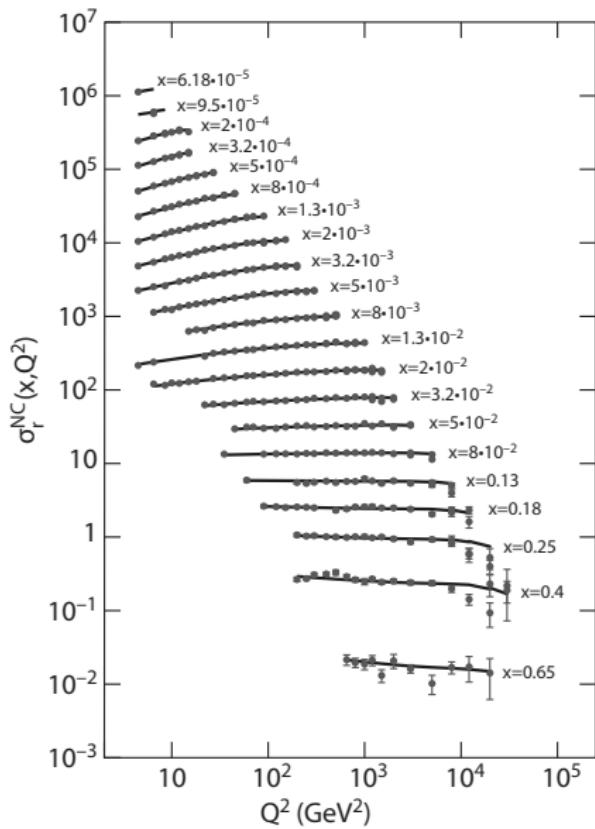
QCD Tests: $e^+e^- \rightarrow$ hadrons



QCD Tests: Quark Confinement

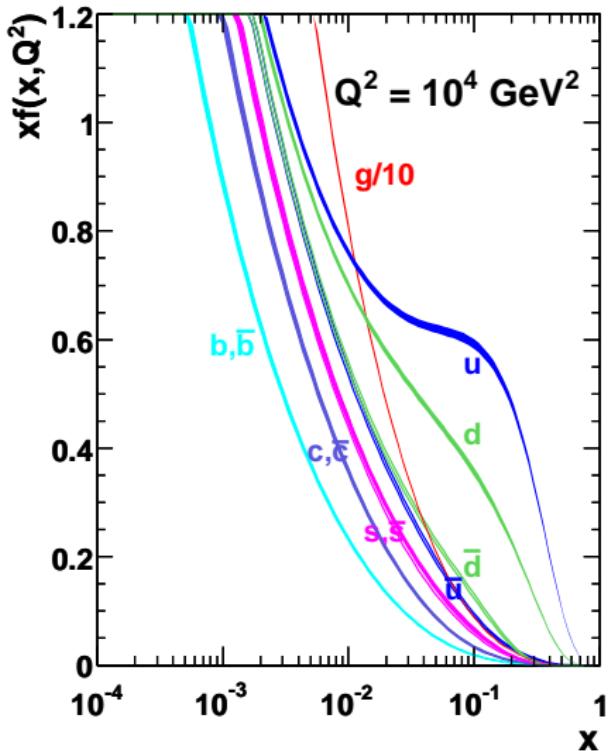
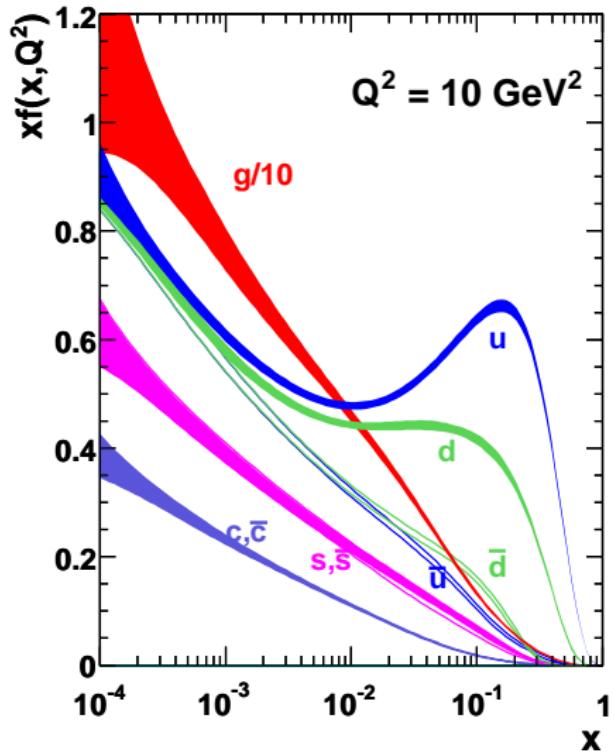


Deeply Inelastic Scattering $\sim f_i^{(a)}(x_a, Q_0^2)$

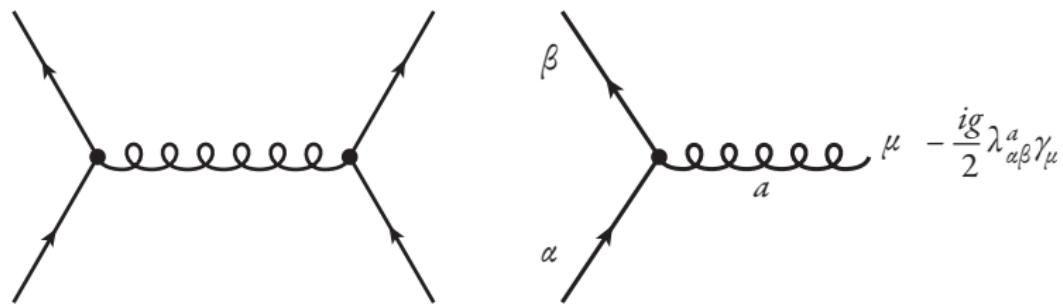


Parton Distribution Functions $f_i(x, Q^2)$

MSTW 2008 NLO PDFs (68% C.L.)



Example reaction: quark–quark scattering



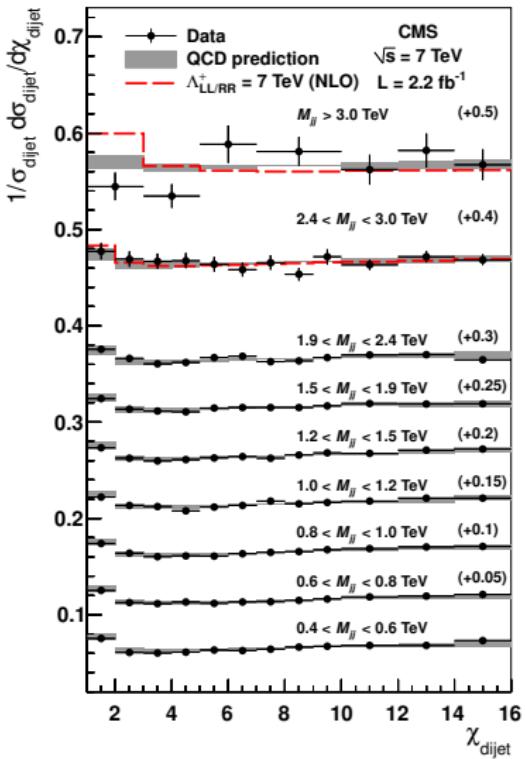
$$\hat{\sigma}(ud \rightarrow ud) = \frac{4\pi\alpha_s^2}{9\hat{s}^2} \cdot \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}$$

$$\leadsto d\sigma/d\Omega^* \propto 1/\sin^4(\theta^*/2)$$

Exercise 4

- (a) Express the $ud \rightarrow ud$ cross section in terms of c.m. angular variables, and verify that the angular distribution is reminiscent of that for Rutherford scattering.
- (b) In the search for new interactions, the angular distribution for quark-quark scattering, inferred from dijet production in $p^\pm p$ collisions, is a sensitive diagnostic. Show that when re-expressed in terms of the variable $\chi = (1 + \cos \theta^*) / (1 - \cos \theta^*)$, the angular distribution for ud scattering is $d\sigma/d\chi \propto \text{constant}$.

Compositeness search in CMS ($|y_{\text{boost}}| < 1.11$)



$$\chi_{\text{dijet}} = e^{|y_1 - y_2|}$$

Parton Luminosity

Hard scattering: $\hat{\sigma} \propto 1/\hat{s}$; Resonance: $\hat{\sigma} \propto \tau$; form

$$\frac{\tau}{\hat{s}} \frac{d\mathcal{L}}{d\tau} \equiv \frac{\tau/\hat{s}}{1 + \delta_{ij}} \int_{\tau}^1 \frac{dx}{x} [f_i^{(a)}(x) f_j^{(b)}(\tau/x) + f_j^{(a)}(x) f_i^{(b)}(\tau/x)]$$

[dimensions σ] measures parton ij luminosity ($\tau = \hat{s}/s$)

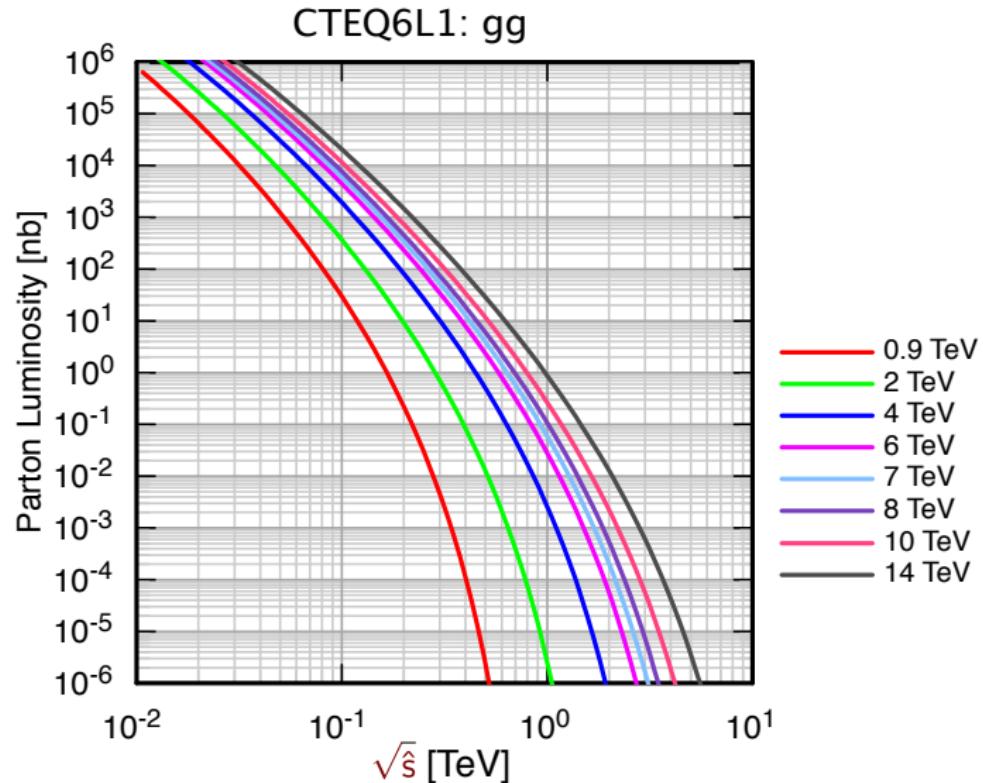
$$\sigma(s) = \sum_{ij} \int_{\tau_0}^1 \frac{d\tau}{\tau} \cdot \frac{\tau}{\hat{s}} \frac{d\mathcal{L}_{ij}}{d\tau} \cdot [\hat{s} \hat{\sigma}_{ij}(\hat{s})]$$

Dimensionless factor $[\dots] \approx$ determined by couplings.
Logarithmic integral typically gives a factor of order unity.

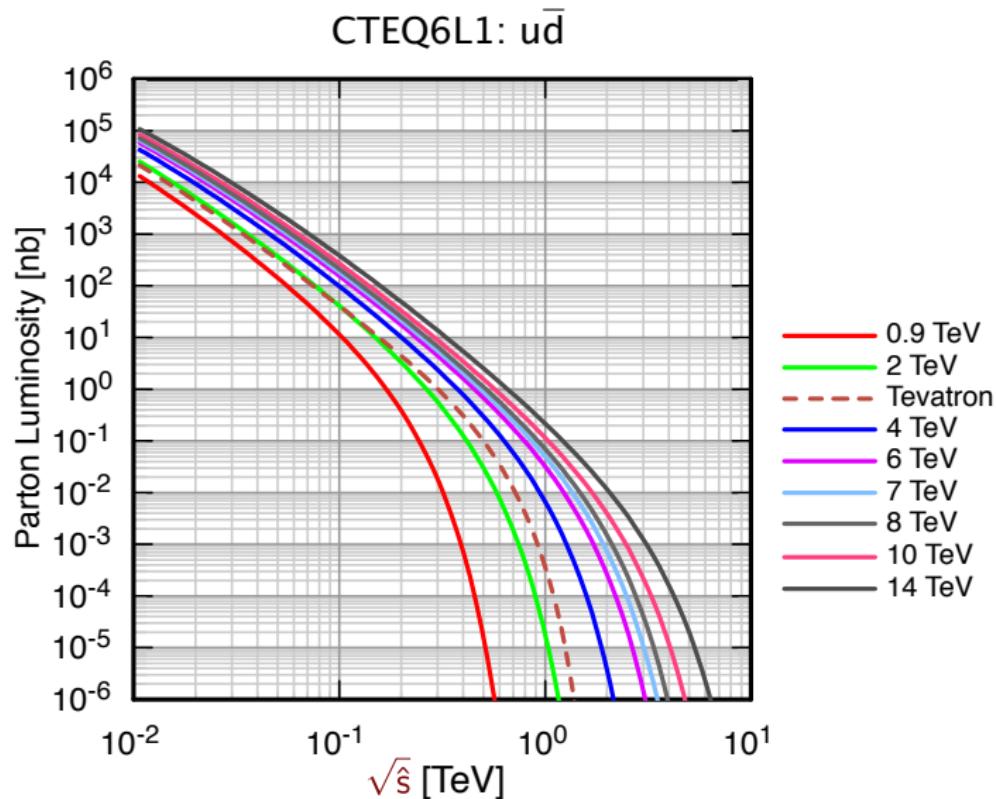
My luminosity page

Stirling luminosities

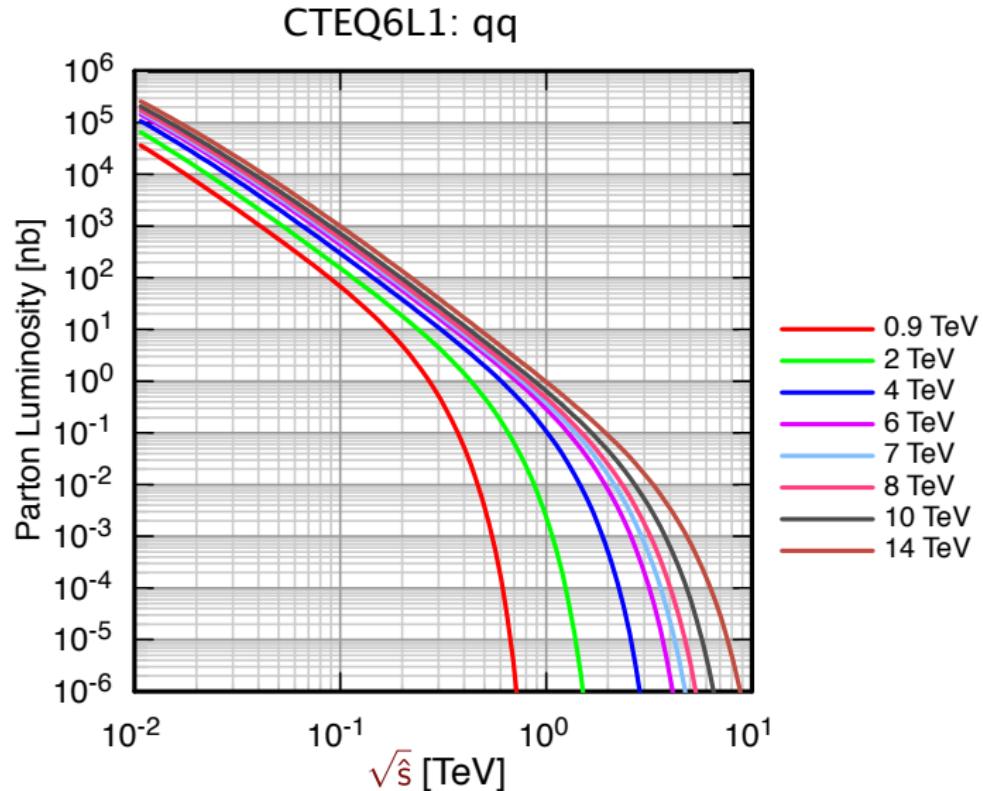
Parton Luminosity: gg



Parton Luminosity: $u\bar{d}$

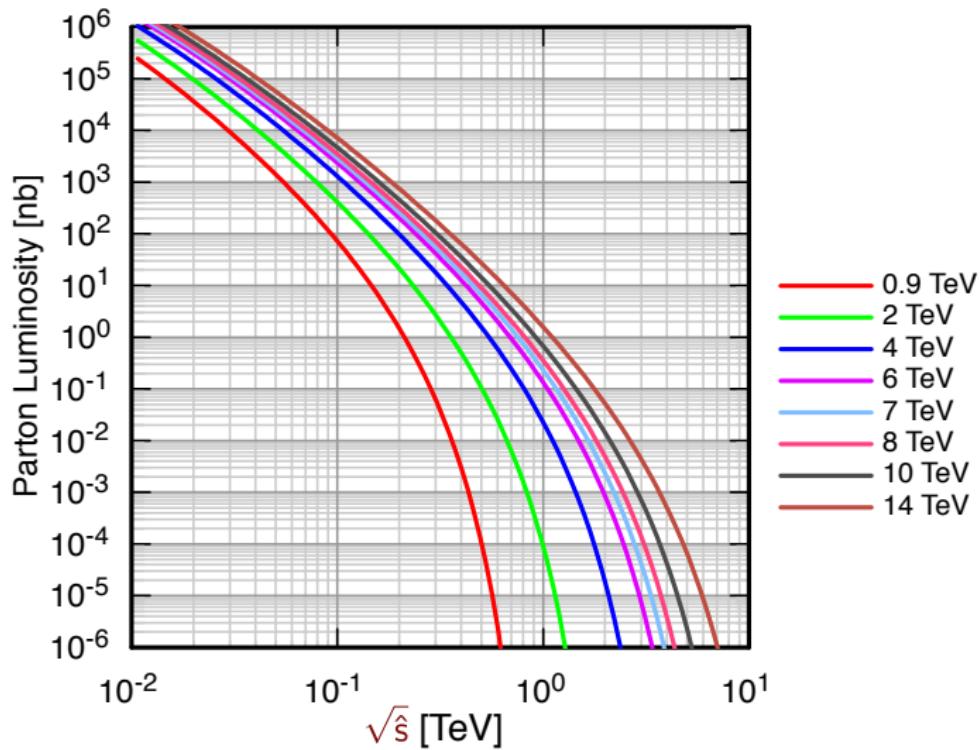


Parton Luminosity (light quarks)

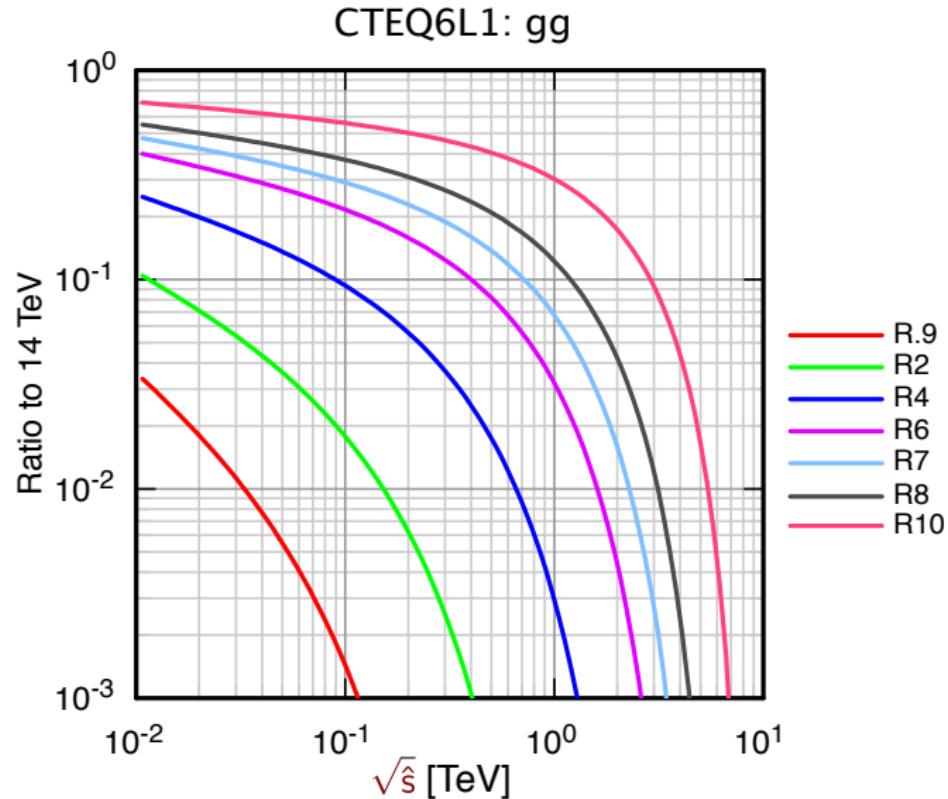


Parton Luminosity: gq

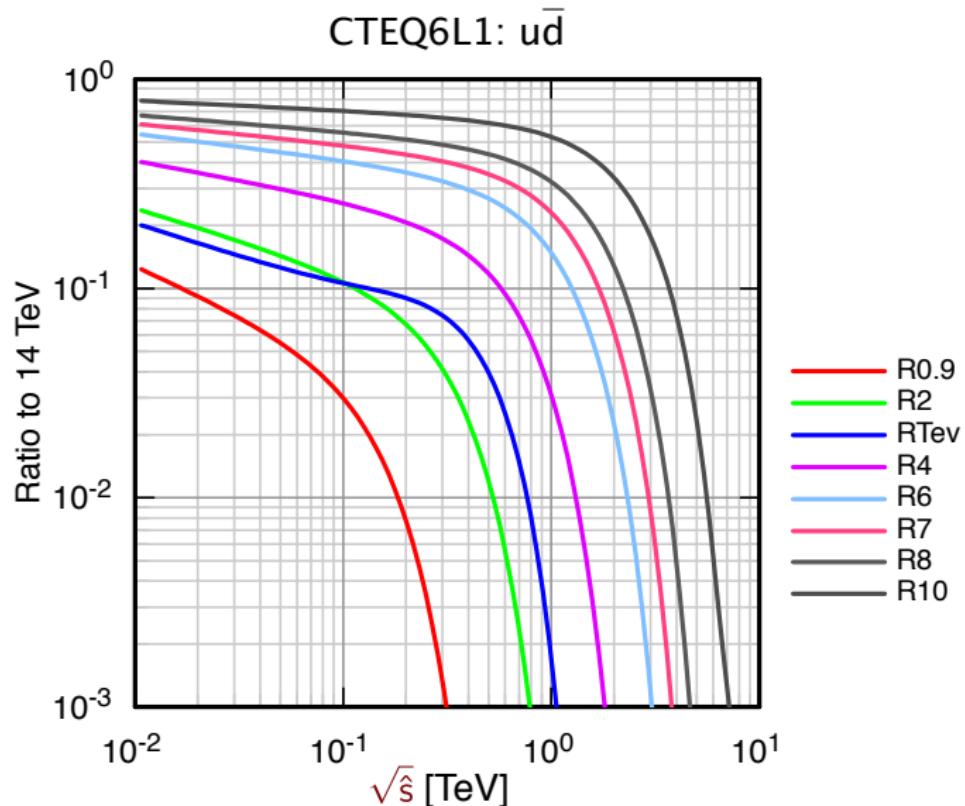
CTEQ6L1: gq



Luminosity Ratios: gg

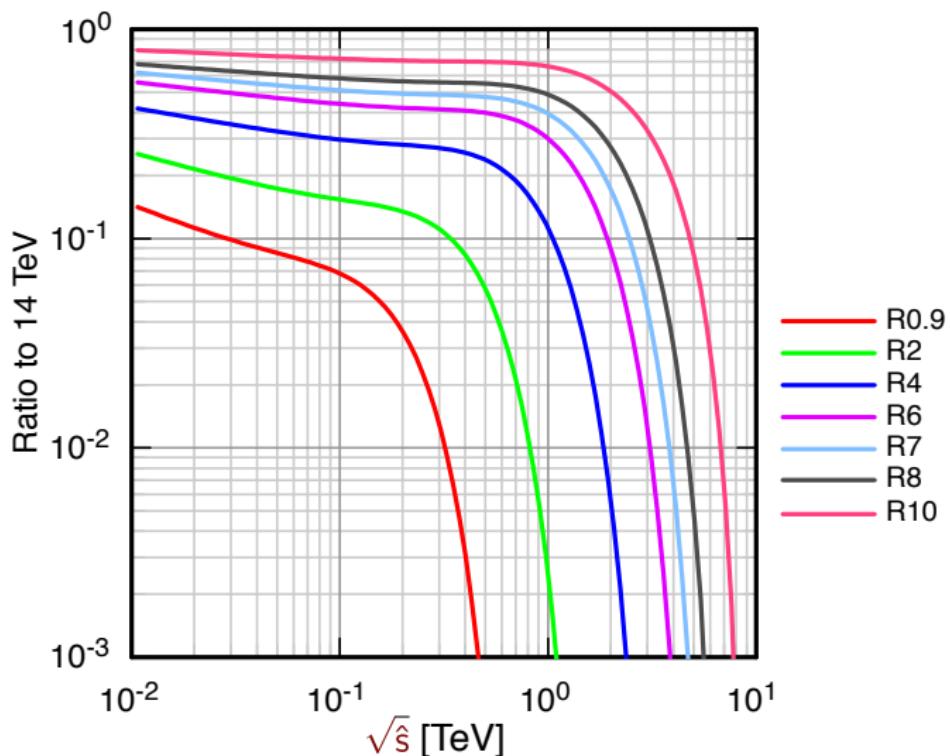


Luminosity Ratios: $u\bar{d}$

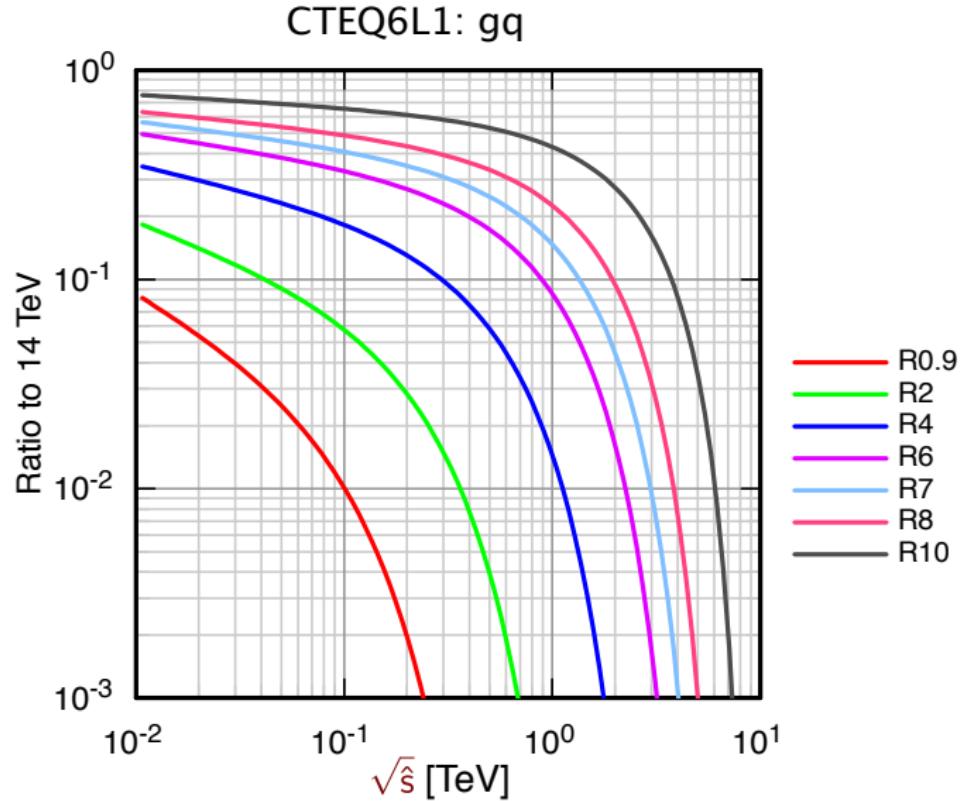


Luminosity Ratios (light quarks)

CTEQ6L1: qq

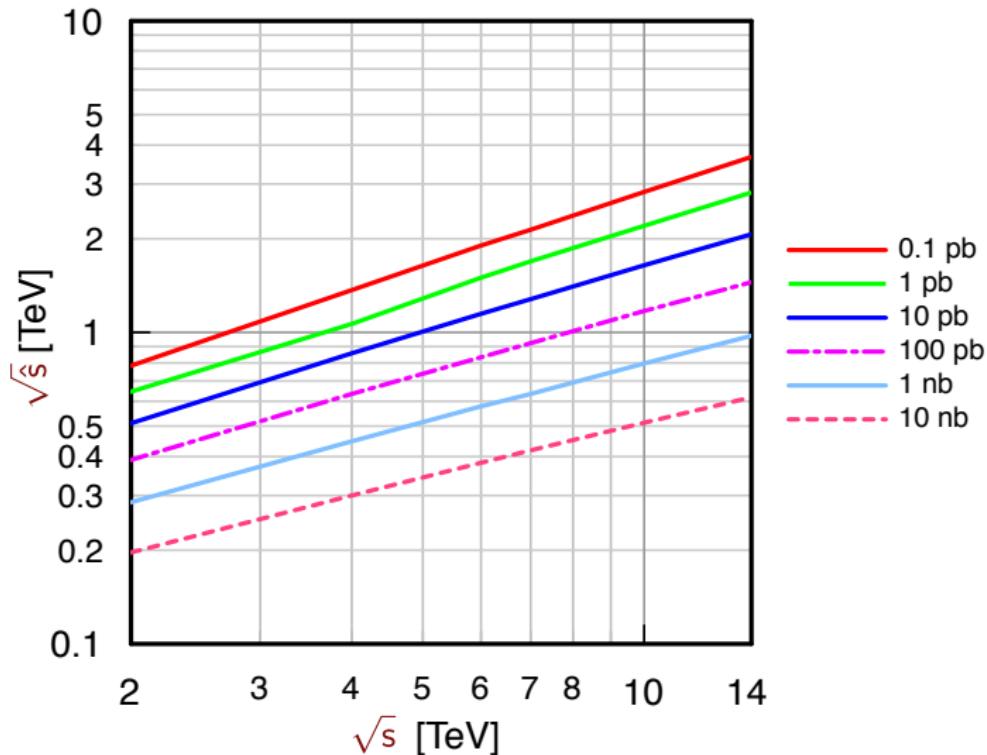


Luminosity Ratios: gq



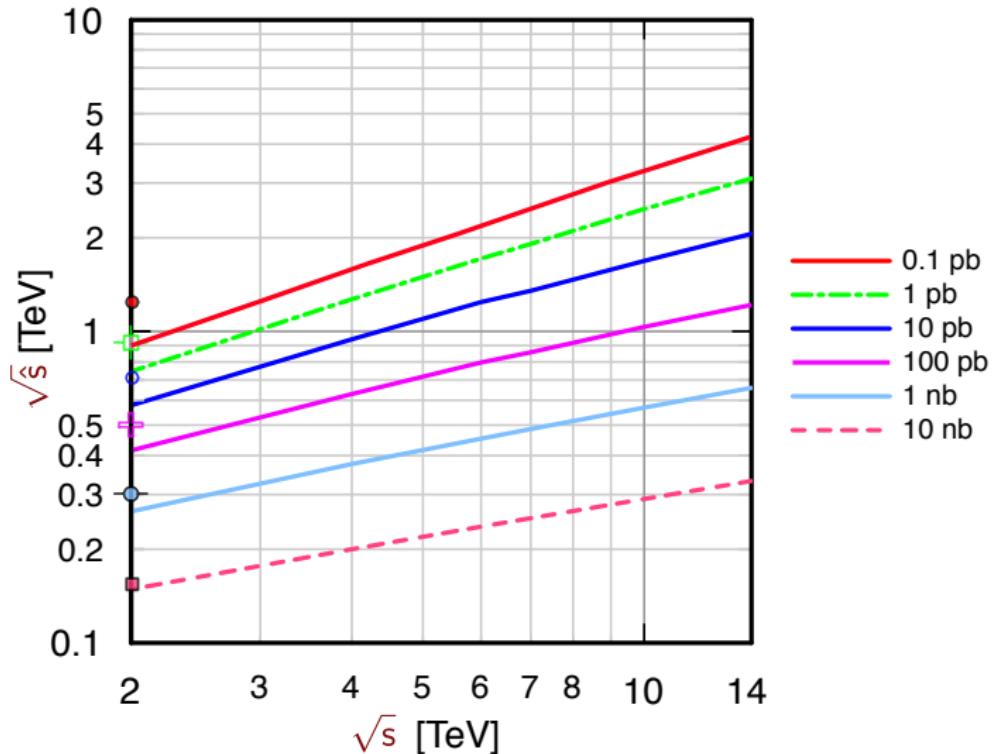
Luminosity Contours: gg

CTEQ6L1: gg



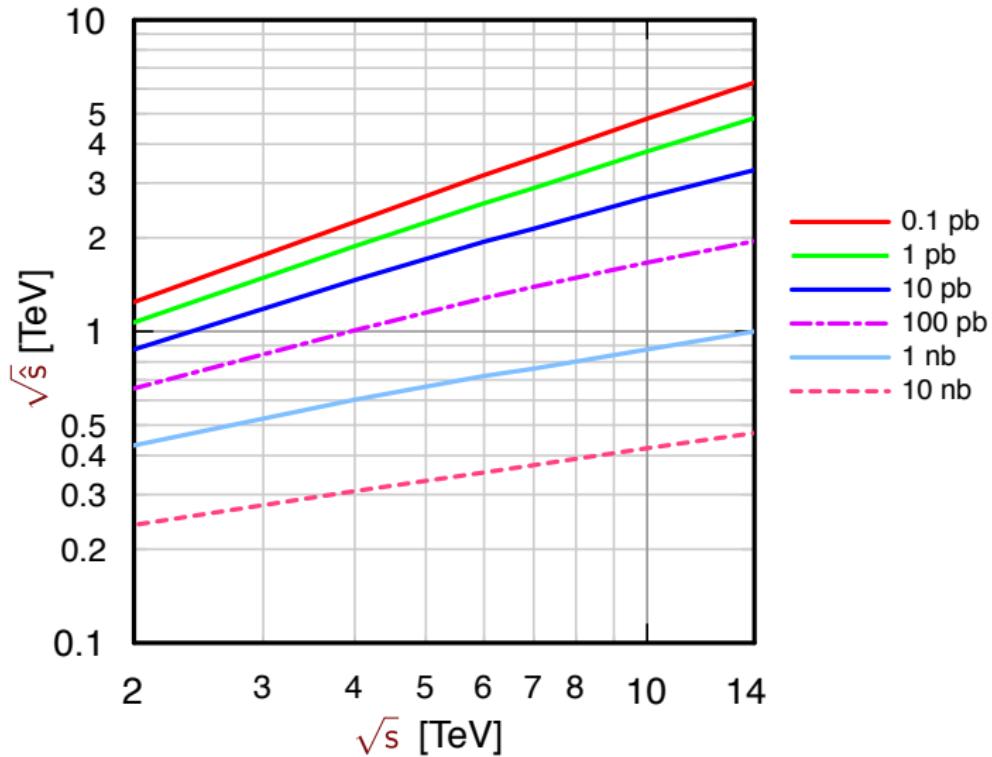
Luminosity Contours: $u\bar{d}$

CTEQ6L1: $u\bar{d}$



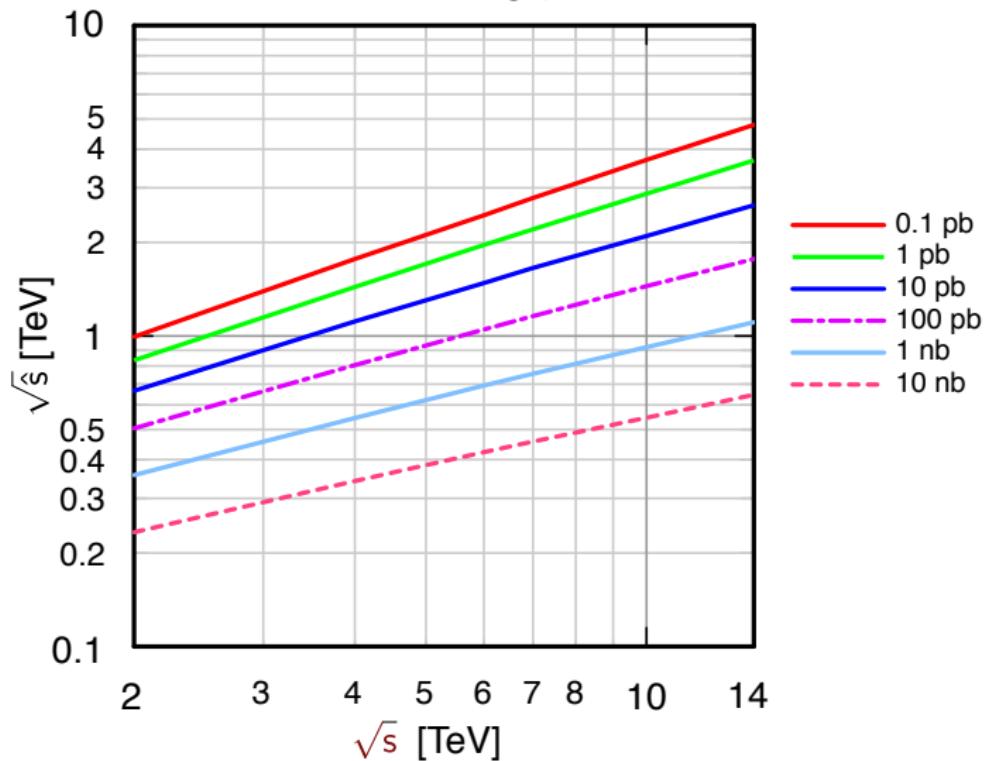
Luminosity Contours (light quarks)

CTEQ6L1: qq



Luminosity Contours: gq

CTEQ6L1: gq



Physics of the Large Hadron Collider

Chris Quigg

Fermilab

Venerable Overview

Supercollider physics

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Eichten *et al.* summarize the motivation for exploring the 1-TeV ($=10^{12}$ eV) energy scale in elementary particle interactions and explore the capabilities of proton-antiproton colliders with beam energies between 1 and 50 TeV. The authors calculate the production rates and characteristics for a number of conventional processes of interest to particle physicists as well as their role as backgrounds to more exotic phenomena. The authors review the theoretical motivation and expected signatures for several new phenomena which may occur on the 1-TeV scale. Their results provide a reference point for the choice of machine parameters and for experiment designs.

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¹For expositions of the current paradigm, see the textbooks by Okun (1981), Perkins (1982), Aitchison and Hey (1982), Leader and Predazzi (1982), Quigg (1983), and Halzen and Martin (1984) and the summer school proceedings edited by Gaillard and Stora (1983).

Anticipating the LHC ...

Unanswered Questions in the Electroweak Theory

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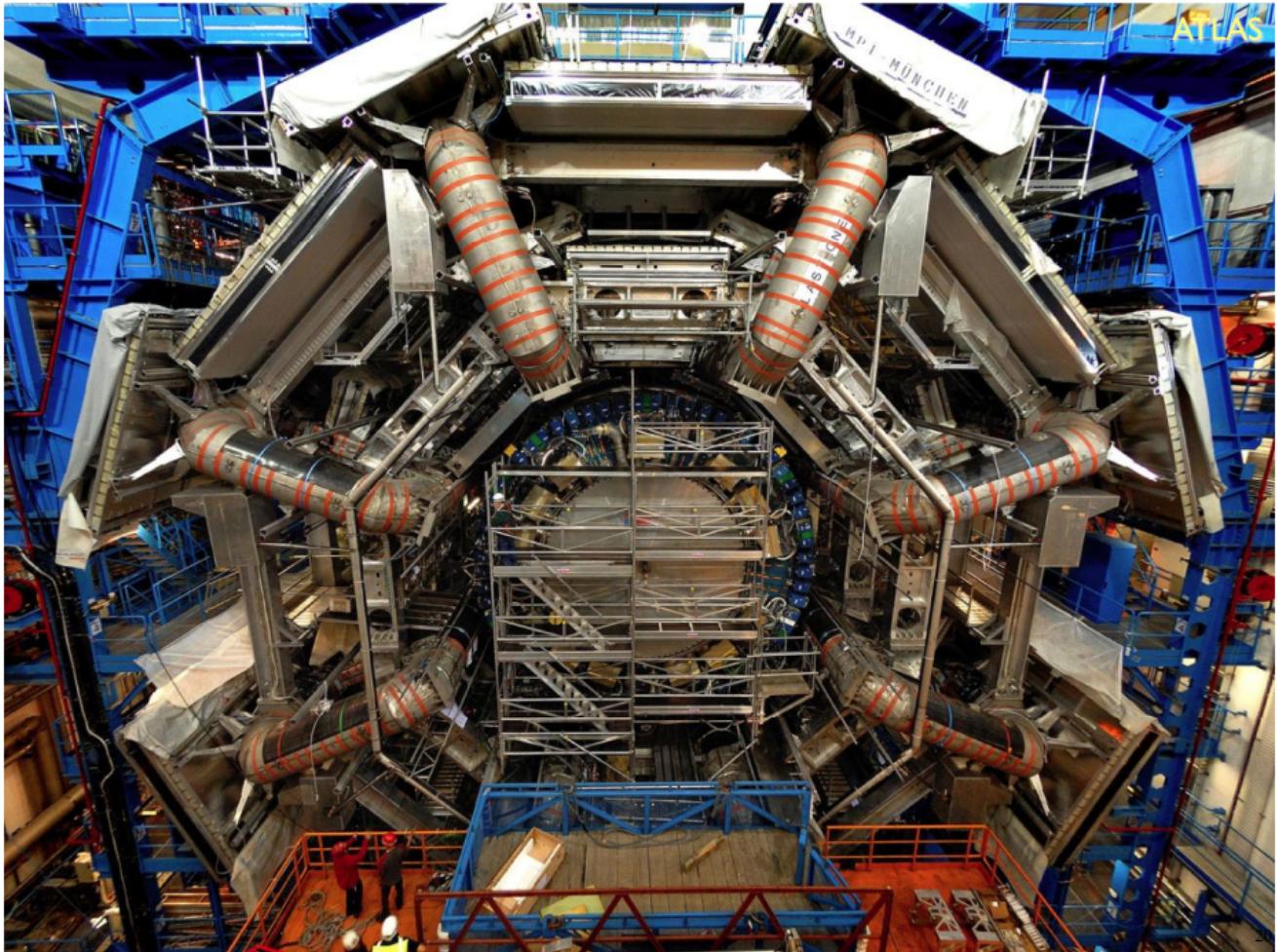
Key Words

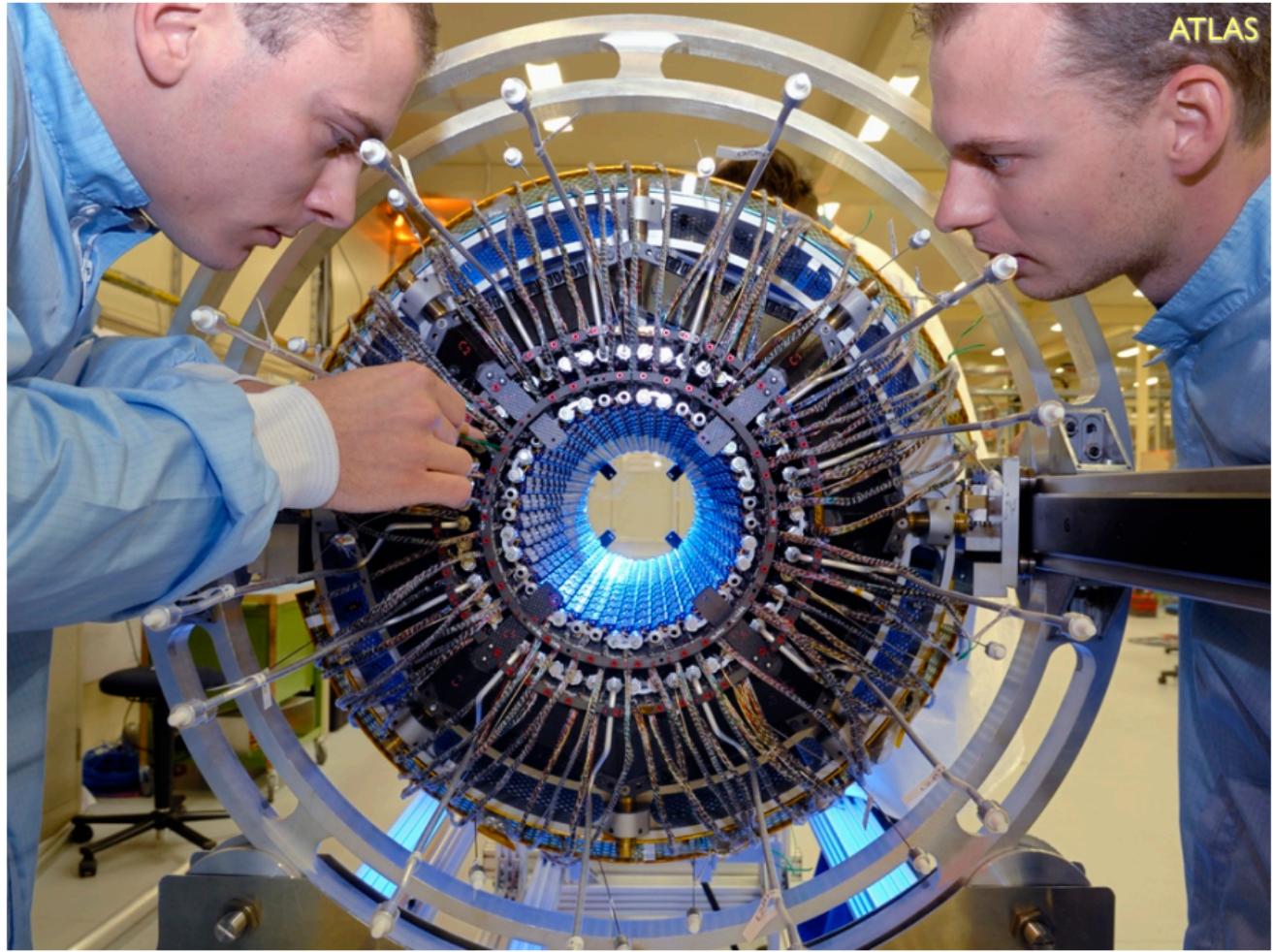
electroweak symmetry breaking, Higgs boson, 1-TeV scale, Large Hadron Collider (LHC), hierarchy problem, extensions to the Standard Model

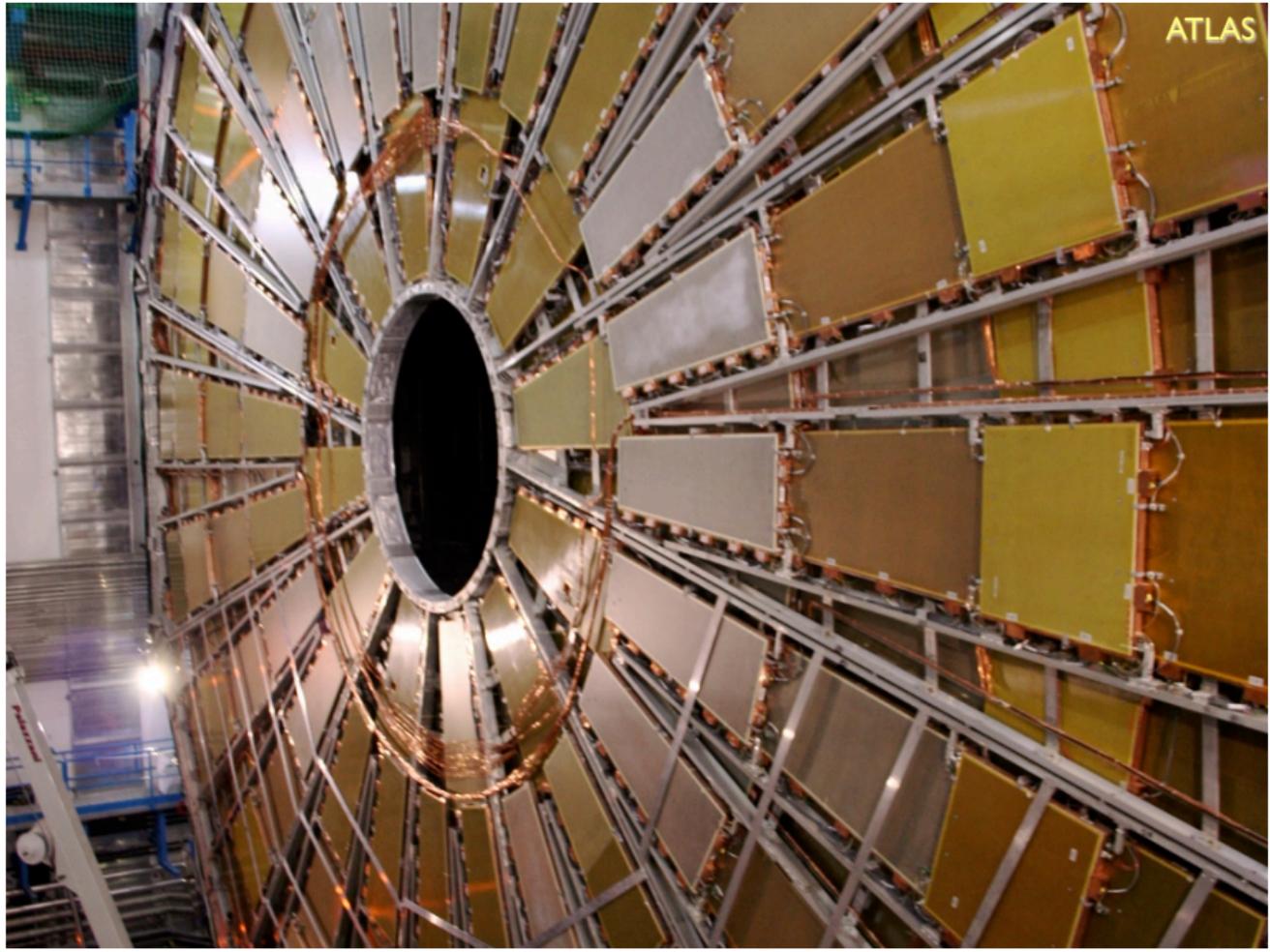
Abstract

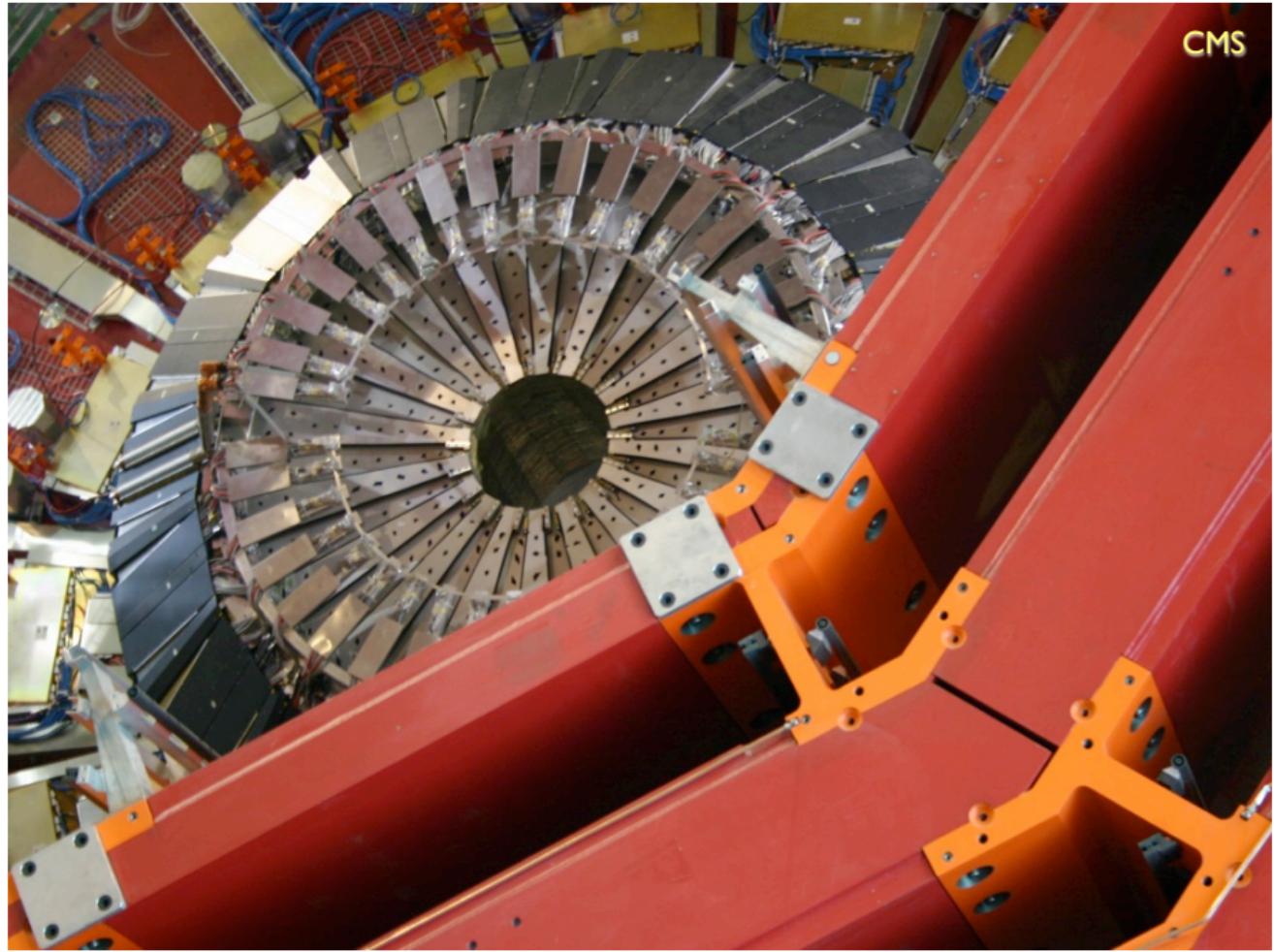
This article is devoted to the status of the electroweak theory on the eve of experimentation at CERN's Large Hadron Collider (LHC). A compact summary of the logic and structure of the electroweak theory precedes an examination of what experimental tests have established so far. The outstanding unconfirmed prediction is the existence of the Higgs boson, a weakly interacting spin-zero agent of electroweak symmetry breaking and the giver of mass to the weak gauge bosons, the quarks, and the leptons. General arguments imply that the Higgs boson or other new physics is required on the 1-TeV energy scale.

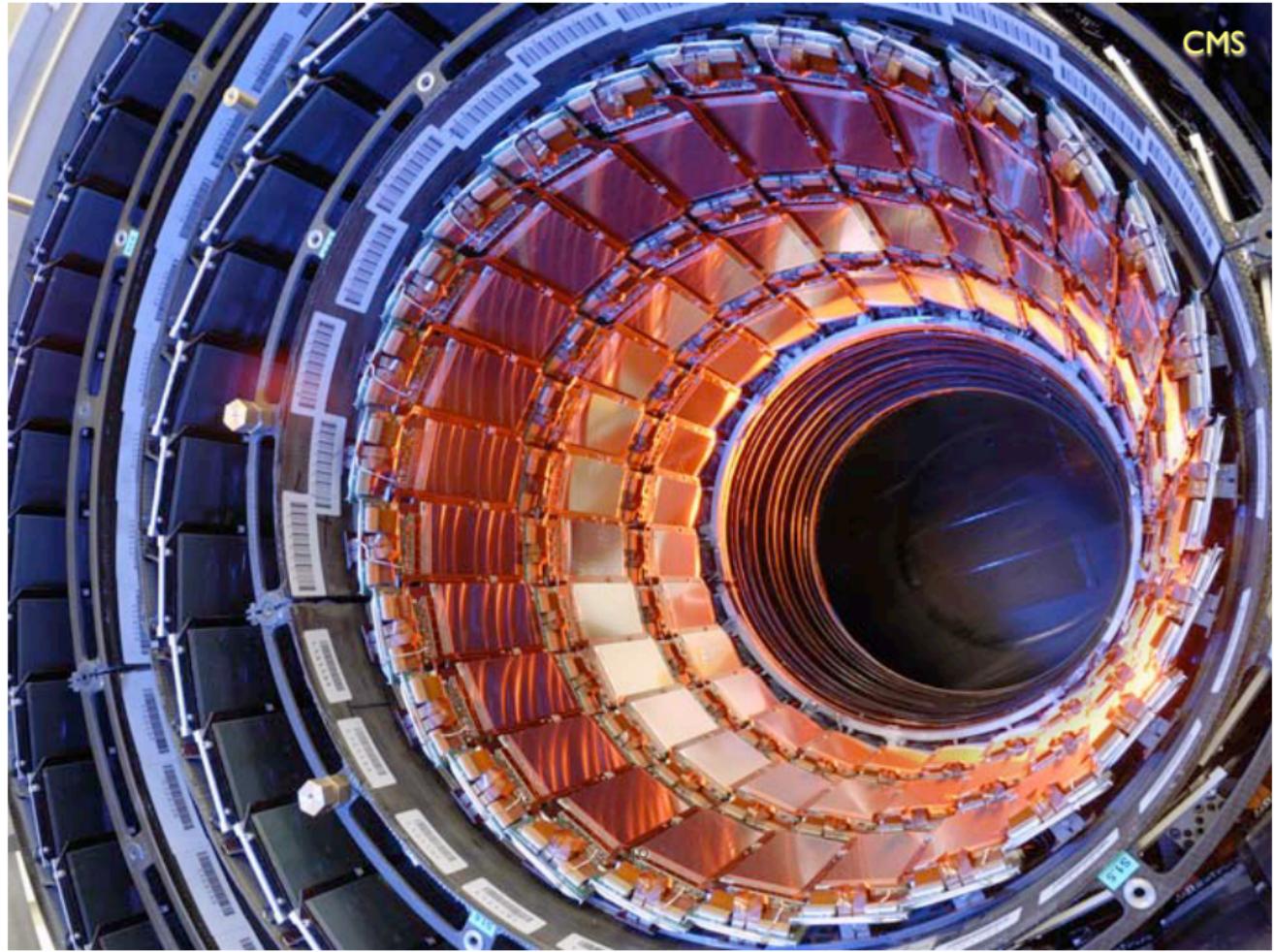
Even if a "standard" Higgs boson is found, new physics will be implicated by many questions about the physical world that the Standard Model cannot answer. Some puzzles and possible resolutions are recalled. The LHC moves experiments squarely into the 1-TeV scale, where answers to important outstanding questions will be found.

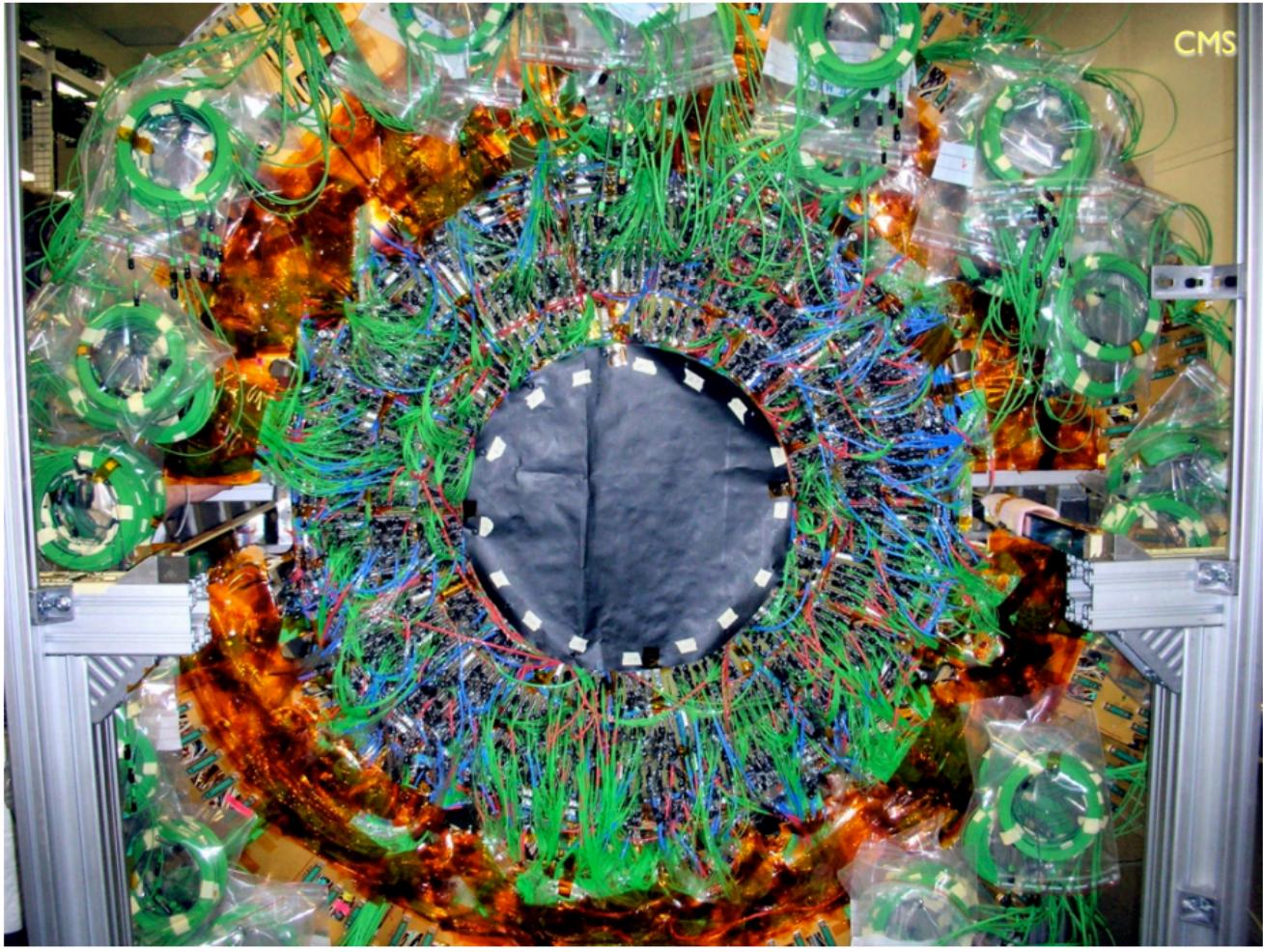


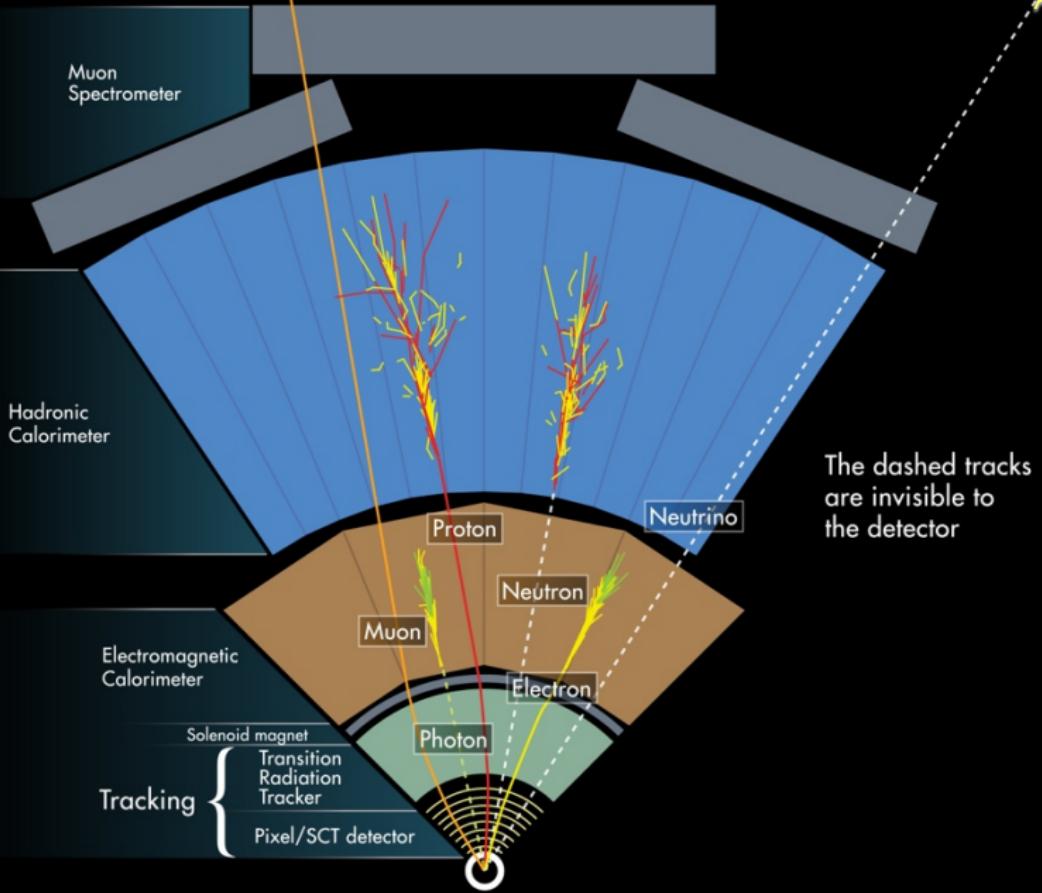












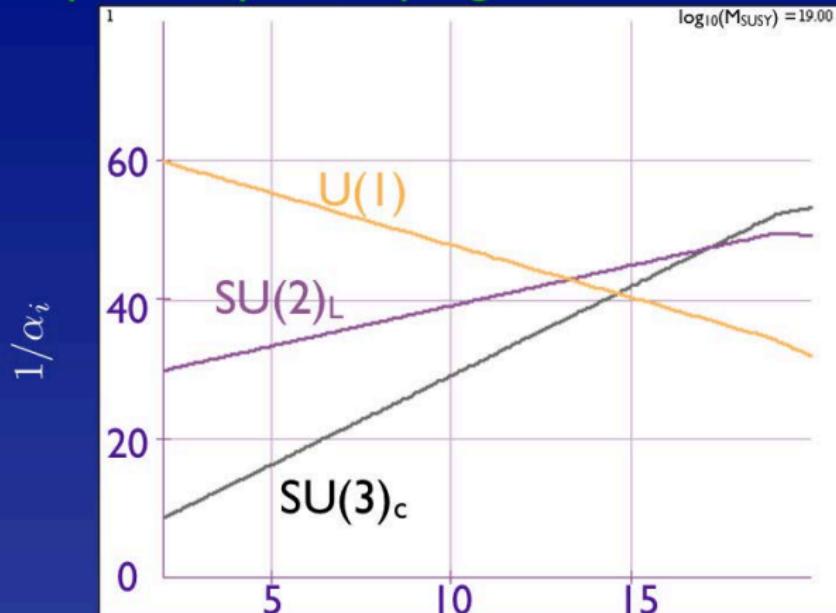
Exercise 5

Explain the response of the ATLAS detector to different particle species, as shown in the graphic on the preceding page.

An interactive slice through the CMS detector animates the response to five particle types.

Coupling-constant Unification

Different running of $U(1)_Y$, $SU(2)_L$, $SU(3)_c$
gives possibility of coupling constant unification

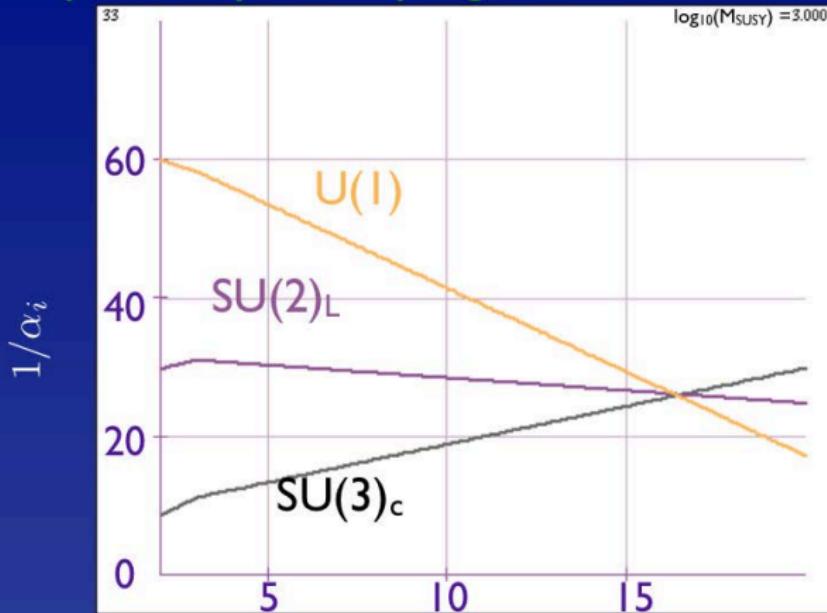


$$\alpha^{-1} = \frac{5}{3}\alpha_1^{-1} + \alpha_2^{-1}$$

$$\log_{10}(E[\text{GeV}])$$

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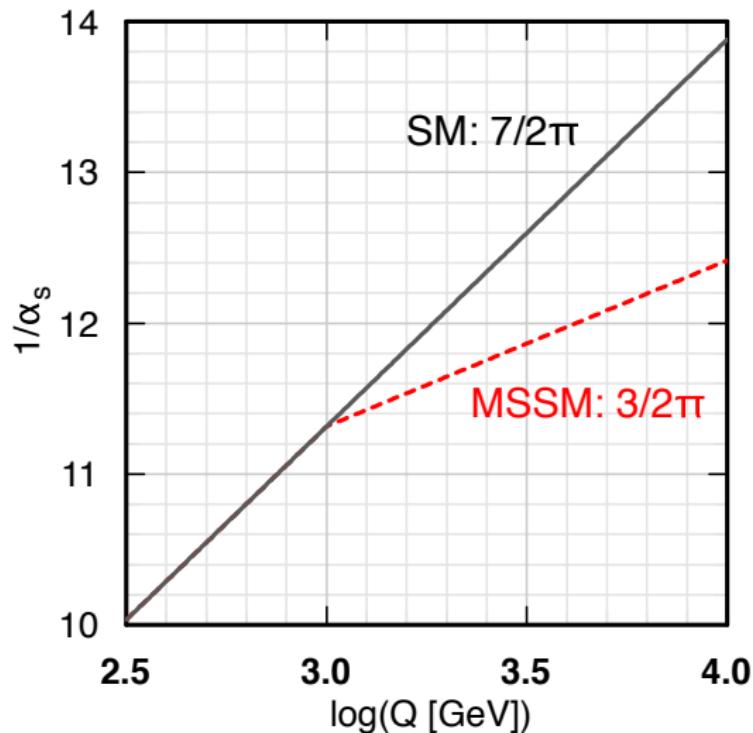


$$\alpha^{-1} = \frac{5}{3}\alpha_1^{-1} + \alpha_2^{-1}$$

$$\log_{10}(E[\text{GeV}])$$

Can LHC See Change in Evolution?

Sensitive to new colored particles



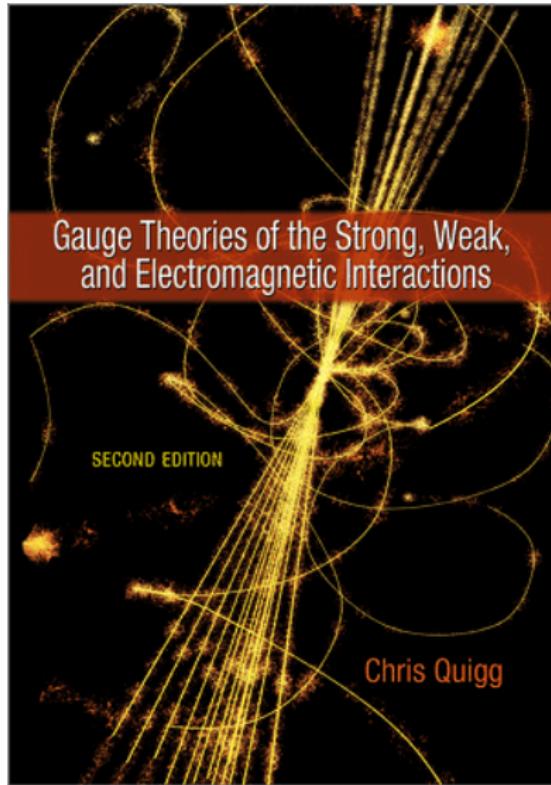
(sharp threshold illustrated)

... also for $\sin^2 \theta_W$

Anyone unfamiliar with electroweak theory?

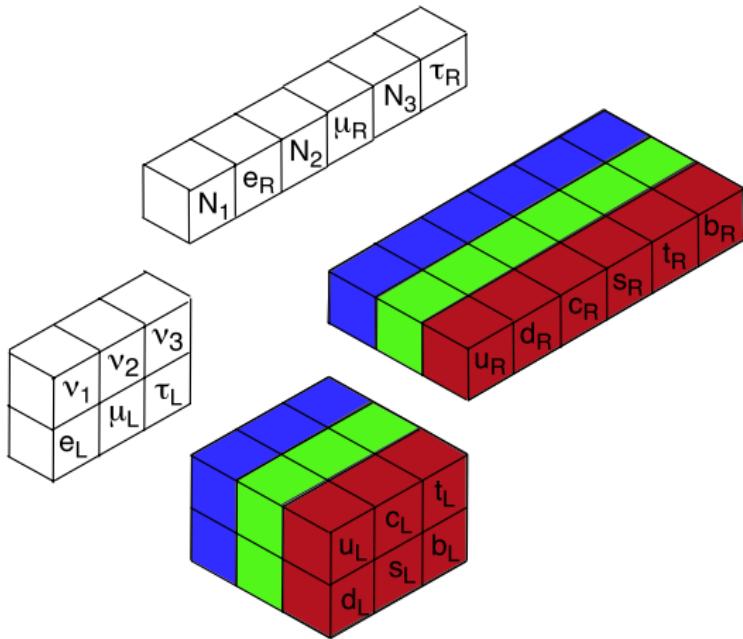
See my five lectures, “The Standard Model—Its Magic and Its Shortcomings,” at the São Paulo school, *Particle Physics in the LHC Era*, April 2013.

Coming soon . . .



Our Picture of Matter

Pointlike constituents ($r < 10^{-18}$ m)



$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \rightarrow SU(3)_c \otimes U(1)_{\text{em}}$$

Unbroken $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ Theory:

As in QED, massless gauge bosons

but weak interaction is short-range

In contrast to QED, massless fermions

Mass term $\mathcal{L}_e = -m_e \bar{e} e = -m_e (\bar{e}_R e_L + \bar{e}_L e_R)$

violates local gauge invariance

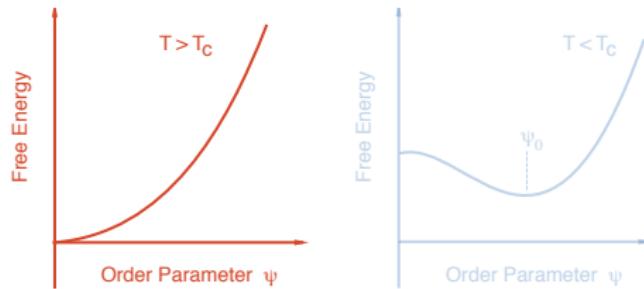
Massive Gauge Boson? *Hiding Symmetry*

Recall **2** miracles of superconductivity:

- No resistance Meissner effect (exclusion of **B**)

Ginzburg–Landau Phenomenology (not a theory from first principles)

normal, resistive charge carriers + superconducting charge carriers



$$\mathbf{B} = 0: \quad G_{\text{super}}(0) = G_{\text{normal}}(0) + \alpha |\psi|^2 + \beta |\psi|^4$$

$$T > T_c : \quad \alpha > 0 \quad \langle |\psi|^2 \rangle_0 = 0$$

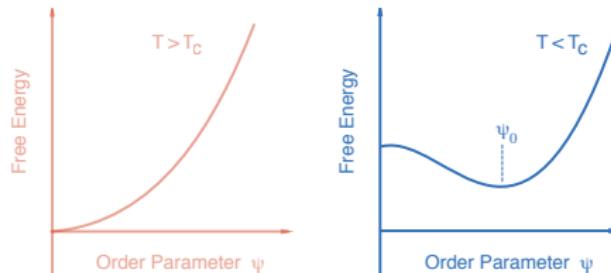
Massive Gauge Boson? *Hiding Symmetry*

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$$T < T_c : \quad \alpha < 0 \quad \langle |\psi|^2 \rangle_0 \neq 0$$

In a nonzero magnetic field . . .

$$G_{\text{super}}(\mathbf{B}) = G_{\text{super}}(0) + \frac{\mathbf{B}^2}{8\pi} + \frac{1}{2m^*} \left| -i\hbar\nabla\psi - \frac{e^*}{c}\mathbf{A}\psi \right|^2$$

$$\left. \begin{array}{l} e^* = -2 \\ m^* \end{array} \right\} \text{of superconducting carriers}$$

Weak, slowly varying field: $\psi \approx \psi_0 \neq 0, \nabla\psi \approx 0$

Variational analysis \leadsto

$$\nabla^2\mathbf{A} - \frac{4\pi e^{*2}}{m^* c^2} |\psi_0|^2 \mathbf{A} = 0$$

wave equation of a *massive photon*

Photon – *gauge boson* – acquires mass within superconductor

origin of Meissner effect

In gauge theory: Brout, Englert, Higgs, Guralnik, Hagen, Kibble

Hide EW Symmetry in Analogy to Ginzburg–Landau

- Electromagnetism is mediated by a massless photon, coupled to the electric charge;
- Mediator of charged-current weak interaction acquires a mass $M_W^2 = \pi\alpha/G_F\sqrt{2}\sin^2\theta_W$,
- Mediator of (new!) neutral-current weak interaction acquires mass $M_Z^2 = M_W^2/\cos^2\theta_W$;
- Massive neutral scalar particle, the Higgs boson, appears, but its mass is not predicted;
- Fermions can acquire mass—values not predicted.

Determine $\sin^2\theta_W$ to predict M_W, M_Z

▶ Vacua

A theory of leptons

$$L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad R \equiv e_R$$

weak hypercharges $Y_L = -1, Y_R = -2$

Gell-Mann–Nishijima connection, $Q = I_3 + \frac{1}{2}Y$

$SU(2)_L \otimes U(1)_Y$ gauge group \Rightarrow gauge fields:

- weak isovector \vec{b}_μ , coupling g

$$b_\mu^\ell = b_\mu^\ell - \varepsilon_{jk\ell} \alpha^j b_\mu^k - (1/g) \partial_\mu \alpha^\ell$$

- weak isoscalar \mathcal{A}_μ , coupling $g'/2$

$$\mathcal{A}_\mu \rightarrow \mathcal{A}_\mu - \partial_\mu \alpha$$

Field-strength tensors

$$F_{\mu\nu}^\ell = \partial_\nu b_\mu^\ell - \partial_\mu b_\nu^\ell + g \varepsilon_{jk\ell} b_\mu^j b_\nu^k, SU(2)_L$$

$$f_{\mu\nu} = \partial_\nu \mathcal{A}_\mu - \partial_\mu \mathcal{A}_\nu, U(1)_Y$$

Interaction Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{leptons}}$$

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} F_{\mu\nu}^\ell F^{\ell\mu\nu} - \frac{1}{4} f_{\mu\nu} f^{\mu\nu},$$

$$\begin{aligned}\mathcal{L}_{\text{leptons}} &= \bar{R} i\gamma^\mu \left(\partial_\mu + i\frac{g'}{2} A_\mu Y \right) R \\ &+ \bar{L} i\gamma^\mu \left(\partial_\mu + i\frac{g'}{2} A_\mu Y + i\frac{g}{2} \vec{\tau} \cdot \vec{b}_\mu \right) L.\end{aligned}$$

Mass term $\mathcal{L}_e = -m_e (\bar{e}_R e_L + \bar{e}_L e_R) = -m_e \bar{e} e$ violates local gauge inv.

Theory: 4 massless gauge bosons $(A_\mu \quad b_\mu^1 \quad b_\mu^2 \quad b_\mu^3)$; Nature: 1 (γ)

Hiding EW Symmetry

Higgs mechanism: relativistic generalization of Ginzburg-Landau superconducting phase transition

- Introduce a complex doublet of scalar fields

$$\phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad Y_\phi = +1$$

- Add to \mathcal{L} (gauge-invariant) terms for interaction and propagation of the scalars,

$$\mathcal{L}_{\text{scalar}} = (\mathcal{D}^\mu \phi)^\dagger (\mathcal{D}_\mu \phi) - V(\phi^\dagger \phi),$$

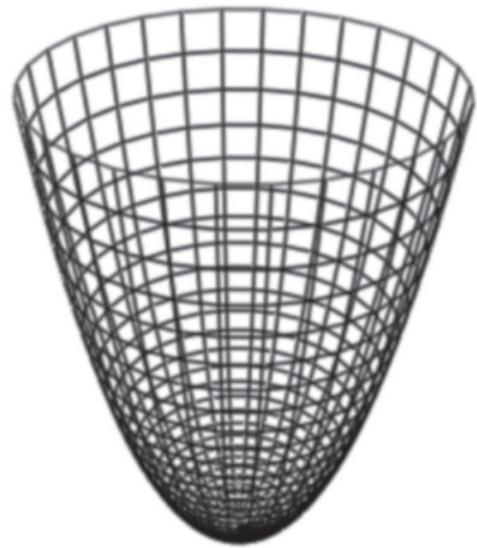
where $\mathcal{D}_\mu = \partial_\mu + i \frac{g'}{2} \mathcal{A}_\mu Y + i \frac{g}{2} \vec{\tau} \cdot \vec{b}_\mu$ and

$$V(\phi^\dagger \phi) = \mu^2 (\phi^\dagger \phi) + |\lambda| (\phi^\dagger \phi)^2$$

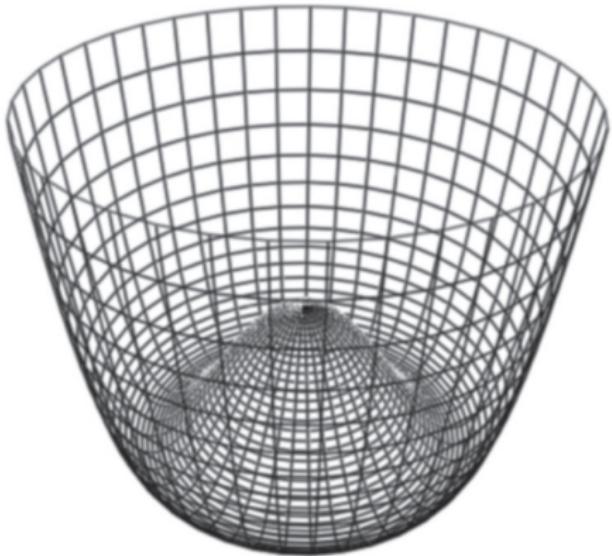
- Add a Yukawa interaction $\mathcal{L}_{\text{Yukawa}} = -\zeta_e [\bar{R}(\phi^\dagger L) + (\bar{L}\phi)R]$

Unique and degenerate vacuum states

(a)



(b)



Origin of Fermion Masses

By decree, Weinberg & Salam add interactions between fermions and scalars that give rise to quark and lepton masses.

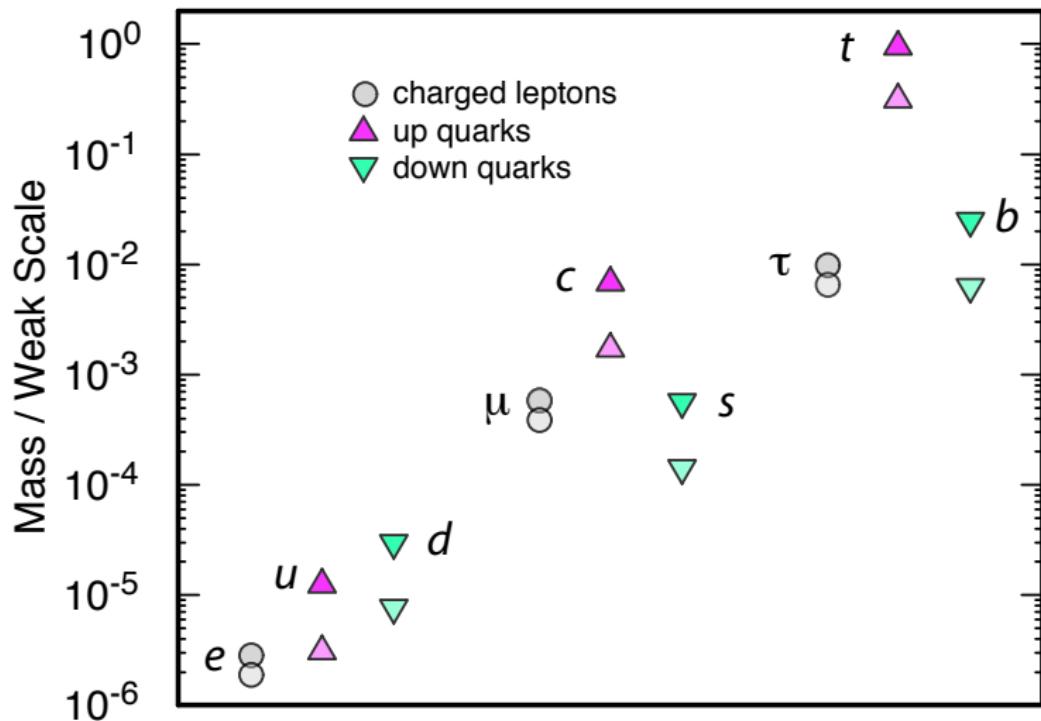
$$\zeta_e [(\bar{e}_L \Phi) e_R + \bar{e}_R (\Phi^\dagger e_L)] \rightsquigarrow m_e = \zeta_e v / \sqrt{2}$$

ζ_e is picked to give right mass, not predicted

Fermion mass implies physics beyond standard model

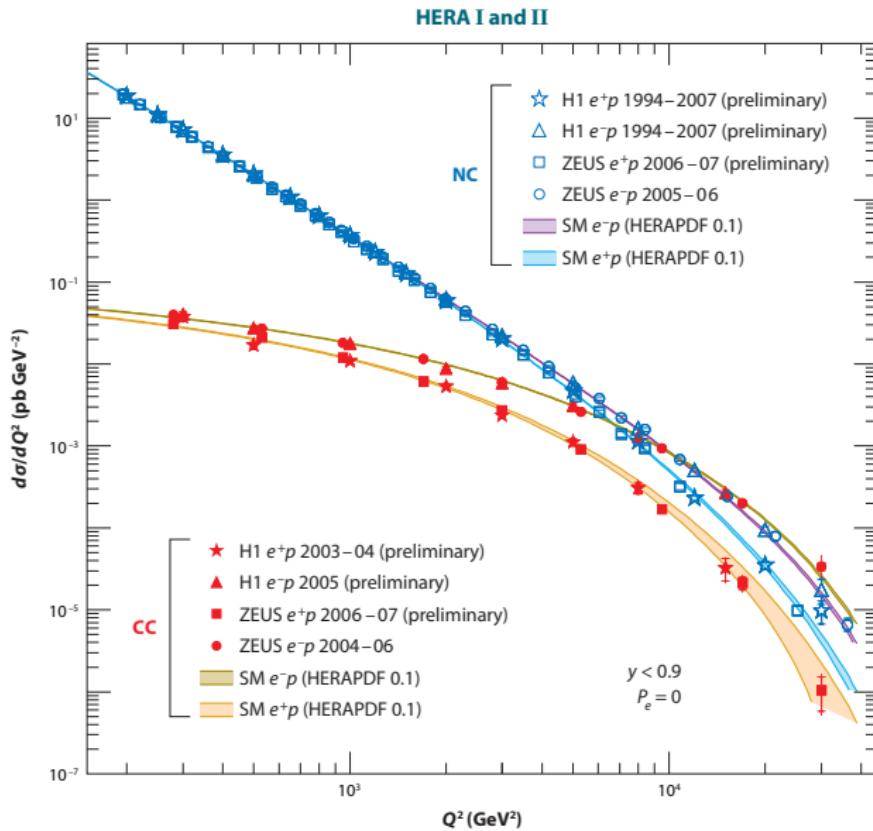
Highly economical, but is it true?

Charged Lepton and Quark Masses

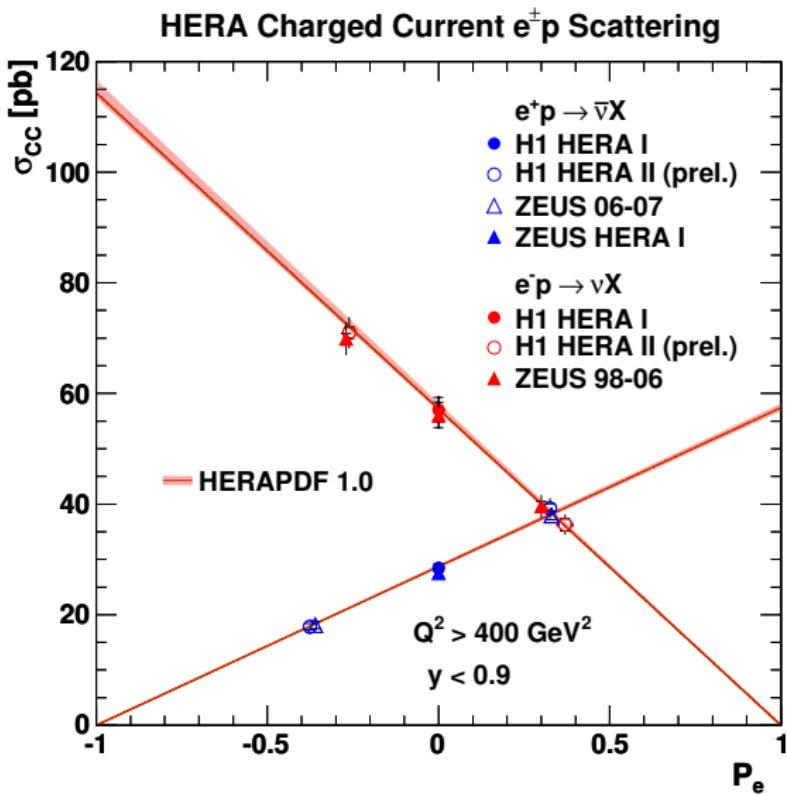


Running mass $m(m) \dots m(U)$

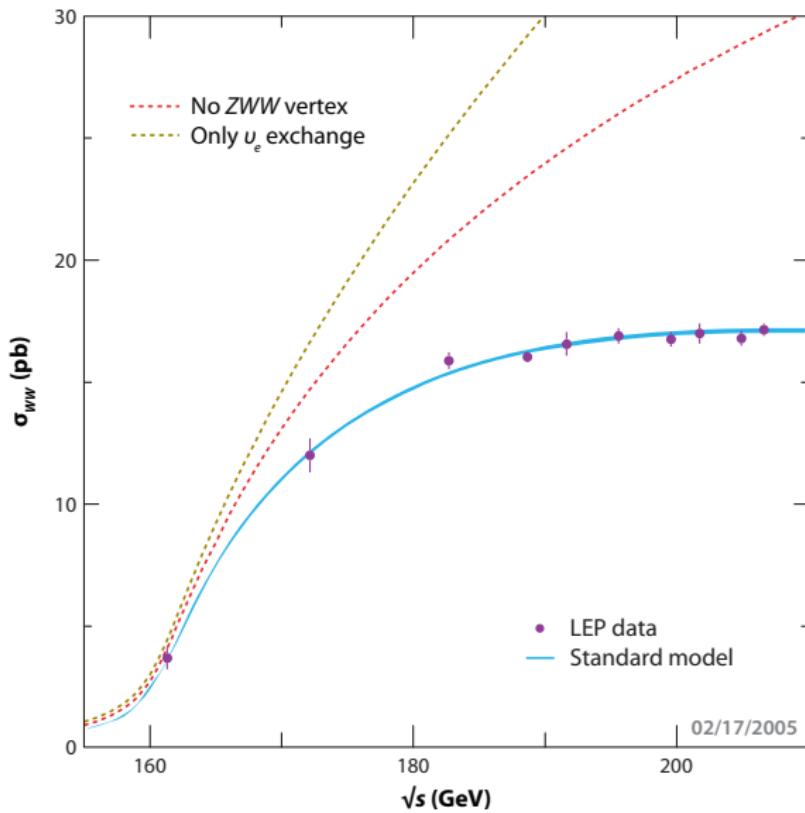
Electroweak theory tests: tree level



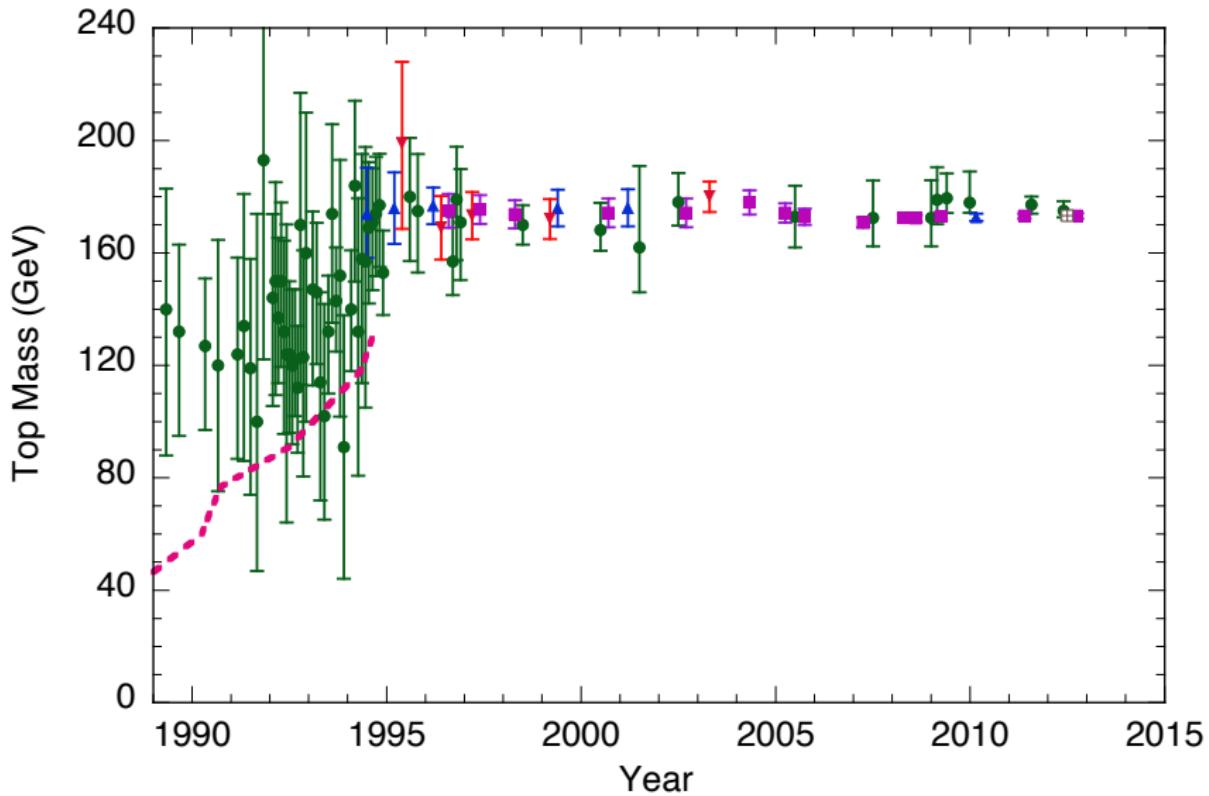
Electroweak theory tests: tree level (no RHCC)



Electroweak theory tests: tree level

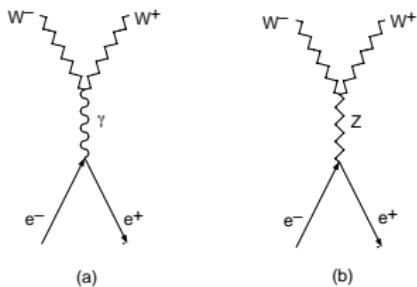


Electroweak theory tests: loop level



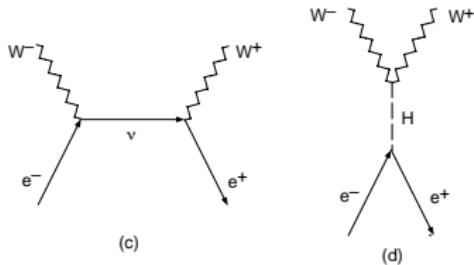
Why a Higgs boson must exist

S-matrix analysis of $e^+e^- \rightarrow W^+W^-$



(a)

(b)



(c)

(d)

Individual $J = 1$ partial-wave amplitudes $\mathcal{M}_\gamma^{(1)}$, $\mathcal{M}_Z^{(1)}$, $\mathcal{M}_\nu^{(1)}$ have unacceptable high-energy behavior ($\propto s$)

... but sum is well-behaved

“Gauge cancellation” observed at LEP2 (Tevatron)

$J = 0$ amplitude exists because electrons have mass, and can be found in “wrong” helicity state

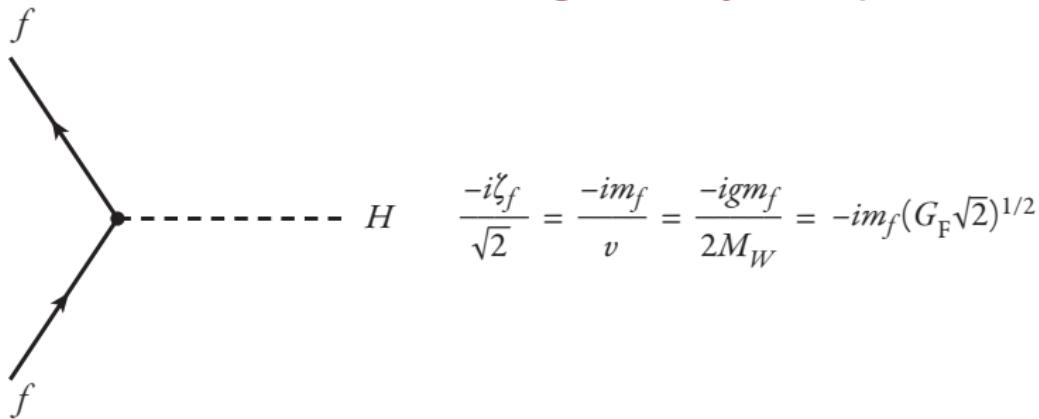
$$\mathcal{M}_\nu^{(0)} \propto s^{\frac{1}{2}} : \text{unacceptable HE behavior}$$

(no contributions from γ and Z)

This divergence is canceled by the Higgs-boson contribution

$\Rightarrow H\bar{e}e$ coupling must be $\propto m_e$,

because “wrong-helicity” amplitudes $\propto m_e$



If the Higgs boson did not exist, something else would have to cure divergent behavior

If gauge symmetry were unbroken . . .

- no Higgs boson; no longitudinal gauge bosons
- no extreme divergences; no wrong-helicity amplitudes

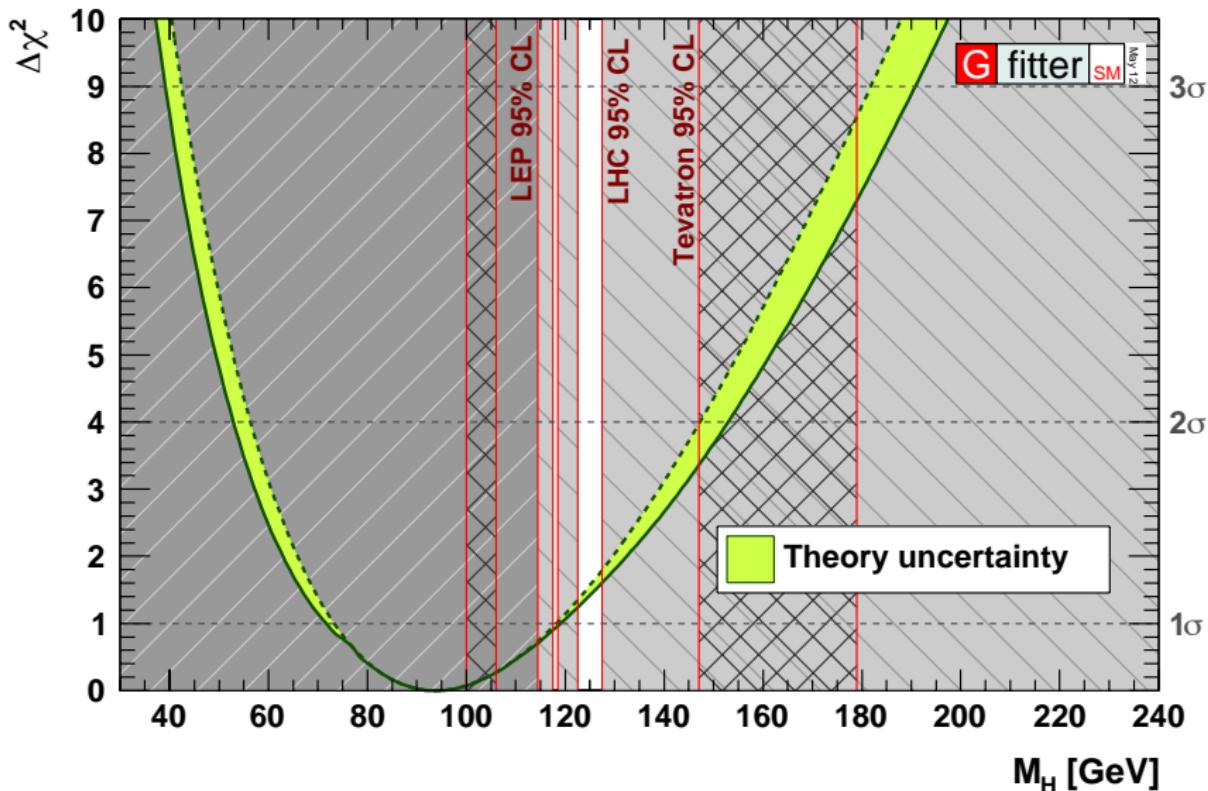
. . . and no viable low-energy phenomenology

In spontaneously broken theory . . .

- gauge structure of couplings eliminates the most severe divergences
- lesser—but potentially fatal—divergence arises because the electron has mass . . . due to SSB
- SSB provides its own cure—the Higgs boson

Similar interplay and compensation *must exist* in any acceptable theory

Electroweak theory tests: Higgs influence



The importance of the 1-TeV scale . . .

EW theory does not predict Higgs-boson mass

▷ *Conditional upper bound from Unitarity*

Compute amplitudes \mathcal{M} for gauge boson scattering at high energies, make a partial-wave decomposition

$$\mathcal{M}(s, t) = 16\pi \sum_J (2J + 1) a_J(s) P_J(\cos \theta)$$

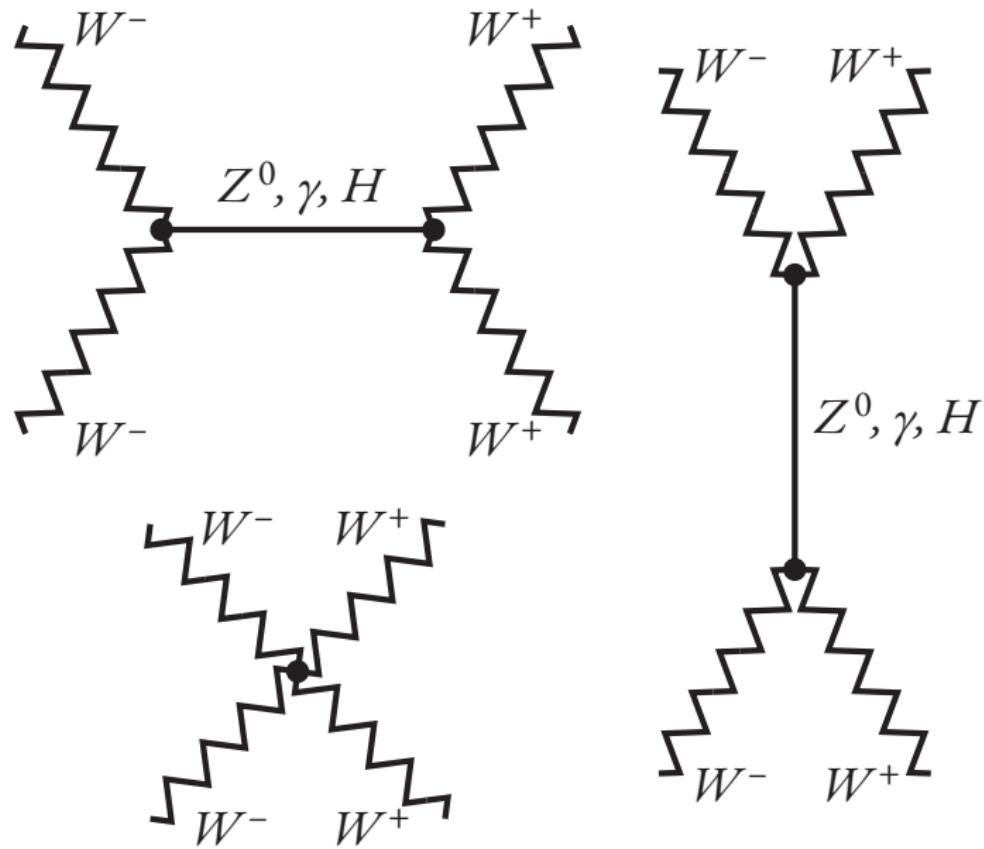
Most channels decouple – pw amplitudes are small at “all” energies – $\forall M_H$.

Four interesting channels:

$$W_L^+ W_L^- \quad Z_L^0 Z_L^0 / \sqrt{2} \quad HH / \sqrt{2} \quad HZ_L^0$$

L : longitudinal, $1/\sqrt{2}$ for identical particles

The importance of the 1-TeV scale ...



The importance of the 1-TeV scale . .

In HE limit, s -wave amplitudes $\propto G_F M_H^2$

$$\lim_{s \gg M_H^2} (a_0) \rightarrow \frac{-G_F M_H^2}{4\pi\sqrt{2}} \cdot \begin{bmatrix} 1 & 1/\sqrt{8} & 1/\sqrt{8} & 0 \\ 1/\sqrt{8} & 3/4 & 1/4 & 0 \\ 1/\sqrt{8} & 1/4 & 3/4 & 0 \\ 0 & 0 & 0 & 1/2 \end{bmatrix}$$

Require that largest eigenvalue respect partial-wave unitarity condition $|a_0| \leq 1$

$$\implies M_H \leq \left(\frac{8\pi\sqrt{2}}{3G_F} \right)^{1/2} \approx 1 \text{ TeV}$$

condition for perturbative unitarity

The importance of the 1-TeV scale . . .

If the bound is respected

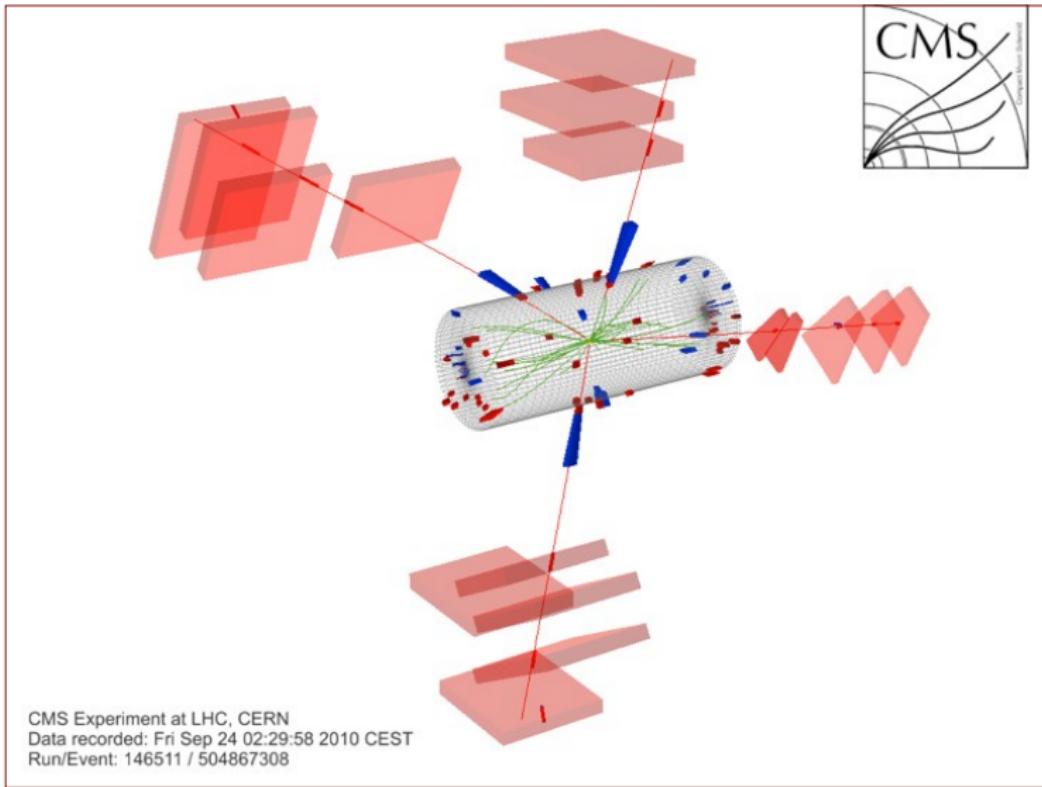
- weak interactions remain weak at all energies
- perturbation theory is everywhere reliable

If the bound is violated

- perturbation theory breaks down
- weak interactions among W^\pm , Z , H become strong on 1-TeV scale

New phenomena are to be found in the EW interactions at energies not much larger than 1 TeV

Heavy Higgs Signature: $ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$



What the Higgs Field Accomplishes

Hides the electroweak symmetry

Gives masses to W and Z
(provides longitudinal components)

Generates fermion masses and mixings
through mysterious Yukawa terms

Makes electroweak theory behave at high energies

Search for the Standard-Model Higgs Boson

$$\Gamma(H \rightarrow f\bar{f}) = \frac{G_F m_f^2 M_H}{4\pi\sqrt{2}} \cdot N_c \cdot \left(1 - \frac{4m_f^2}{M_H^2}\right)^{3/2}$$

$\propto M_H$ in the limit of large Higgs mass; $\propto \beta^3$ for scalar

$$\Gamma(H \rightarrow W^+ W^-) = \frac{G_F M_H^3}{32\pi\sqrt{2}} (1-x)^{1/2} (4-4x+3x^2) \quad x \equiv 4M_W^2/M_H^2$$

$$\Gamma(H \rightarrow Z^0 Z^0) = \frac{G_F M_H^3}{64\pi\sqrt{2}} (1-x')^{1/2} (4-4x'+3x'^2) \quad x' \equiv 4M_Z^2/M_H^2$$

asymptotically $\propto M_H^3$ and $\frac{1}{2}M_H^3$, respectively

$2x^2$ and $2x'^2$ terms \Leftrightarrow decays into transverse gauge bosons

Dominant decays for large M_H : pairs of longitudinal weak bosons

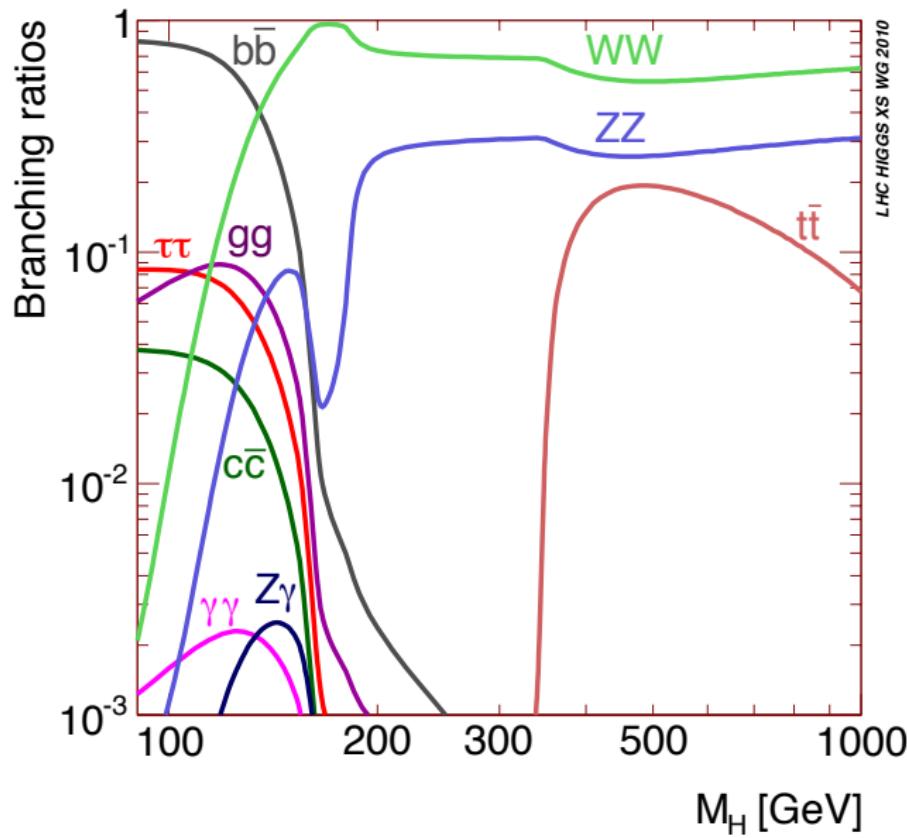
Exercise 6

Compute the decay rate for the Higgs boson into fermion pairs given on the previous page,

$$\Gamma(H \rightarrow f\bar{f}) = \frac{G_F m_f^2 M_H}{4\pi\sqrt{2}} \cdot N_c \cdot \left(1 - \frac{4m_f^2}{M_H^2}\right)^{3/2},$$

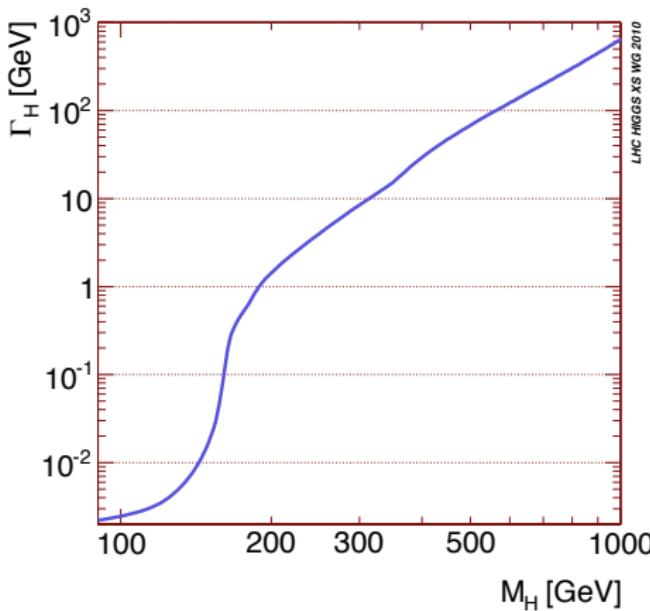
using the Feynman rule given above.

SM Higgs Boson Branching Fractions



Total width of the standard-model Higgs boson

$$\Gamma_H(M_H = 126 \text{ GeV}) = 4.2 \text{ MeV}$$



Below W^+W^- threshold, $\Gamma_H \lesssim 1 \text{ GeV}$

Far above W^+W^- threshold, $\Gamma_H \propto M_H^3$

A few words on Higgs production . . .

$e^+e^- \rightarrow H$: hopelessly small

$\mu^+\mu^- \rightarrow H$: scaled by $(m_\mu/m_e)^2 \approx 40\,000$

$e^+e^- \rightarrow HZ$: prime channel

Hadron colliders:

$gg \rightarrow H \rightarrow b\bar{b}$: background ?!

$gg \rightarrow H \rightarrow \tau\tau, \gamma\gamma$: rate ?!

$gg \rightarrow H \rightarrow W^+W^-$: best Tevatron sensitivity

$\bar{p}p \rightarrow H(W, Z)$: prime Tevatron channel for light Higgs

At the LHC:

Many channels accessible, search sensitive up to 1 TeV

Higgs search in e^+e^- collisions

$\sigma(e^+e^- \rightarrow H \rightarrow \text{all})$ is *minute*, $\propto m_e^2$

Even narrowness of low-mass H is not enough to make it visible . . . Sets aside a traditional strength of e^+e^- machines—*pole physics*

Most promising:
associated production $e^+e^- \rightarrow HZ$
(has no small couplings)

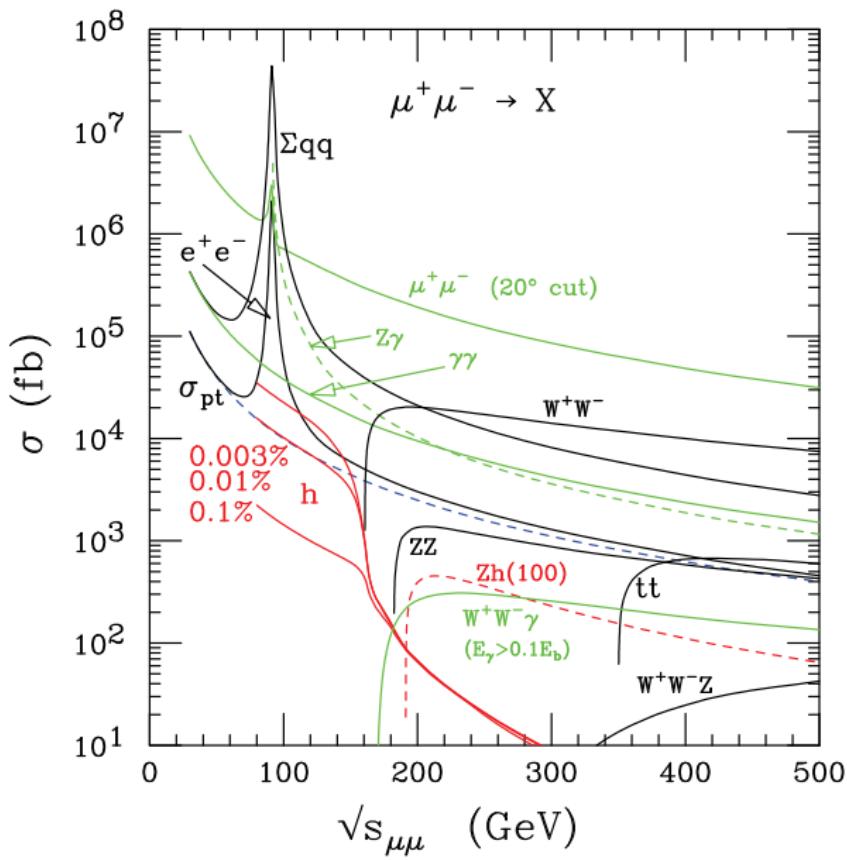


$$\sigma = \frac{\pi \alpha^2}{24\sqrt{s}} \frac{K(K^2 + 3M_Z^2)[1 + (1 - 4x_W)^2]}{(s - M_Z^2)^2 \ x_W^2(1 - x_W)^2}$$

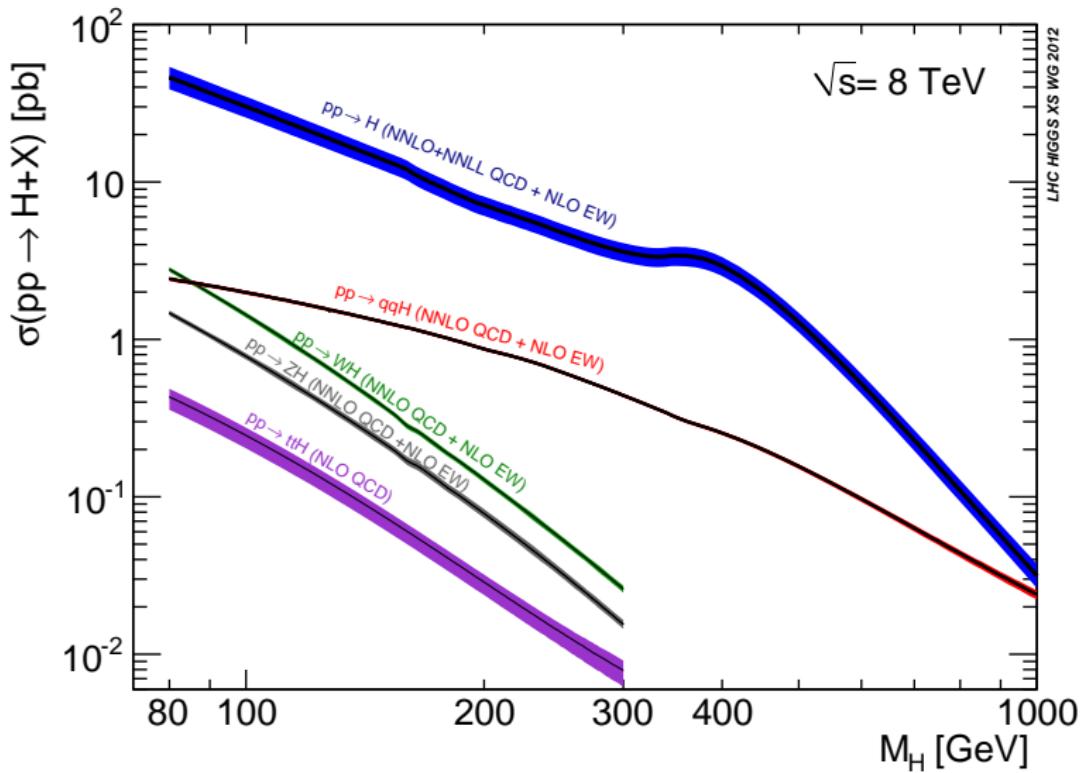
K : c.m. momentum of H

$x_W \equiv \sin^2 \theta_W$

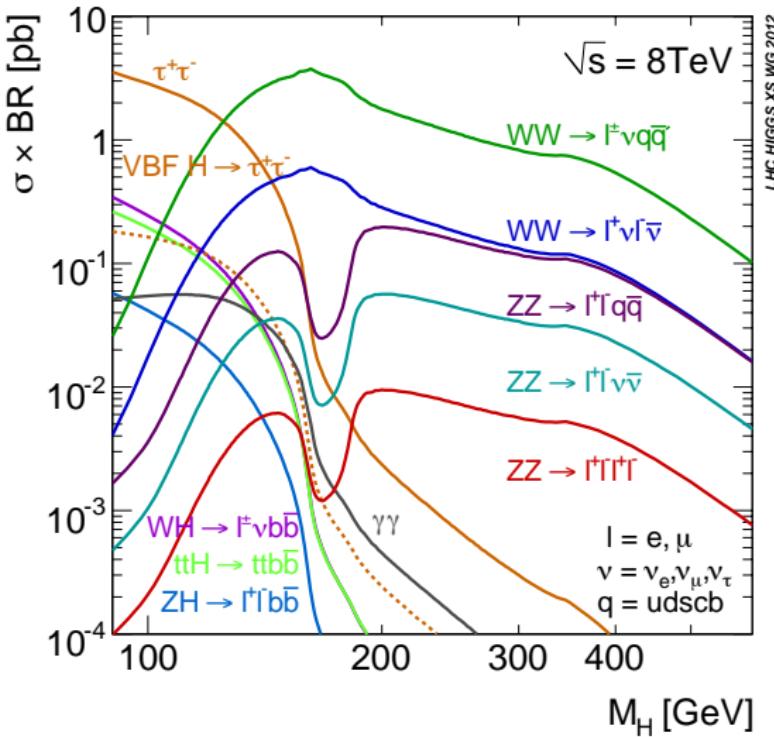
$\ell^+ \ell^- \rightarrow X \dots$



Higgs-boson production at the LHC: 8 TeV



Higgs-boson production and decay: 8 TeV





ATLAS $\gamma\gamma$ signal evolution

CMS 4μ signal evolution

Evolution of evidence at the LHC

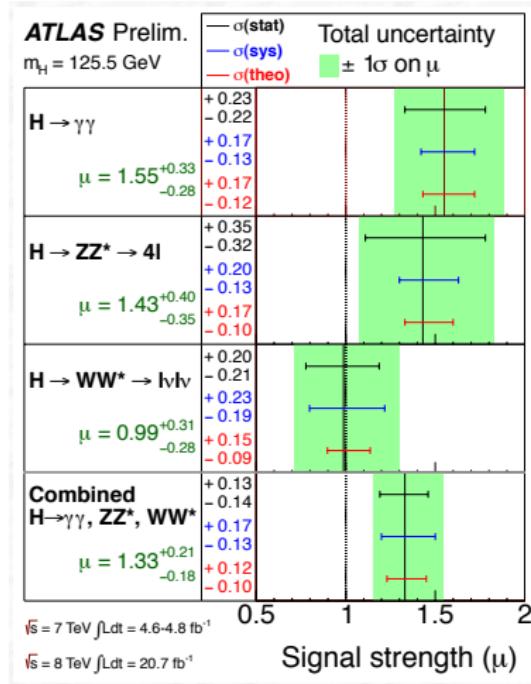
Evidence is developing as it would for
a “standard-model” Higgs boson

Unstable neutral particle near 126 GeV

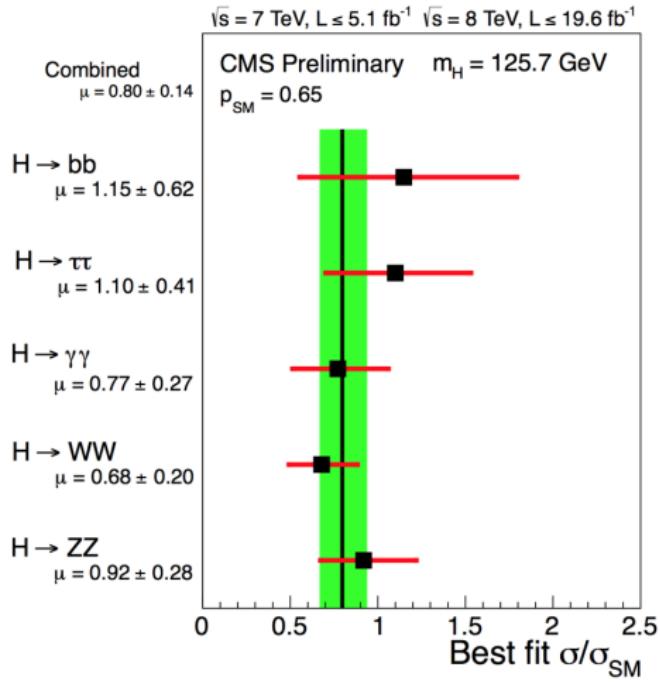
decays to $\gamma\gamma$, W^+W^- , ZZ
likely (dominantly) spin-parity 0^+
evidence for $\tau^+\tau^-$, $b\bar{b}$

Consistency with Standard-Model Higgs

ATLAS twiki



CMS twiki



Why Electroweak Symmetry Breaking Matters

What would the world be like, without a (Higgs) mechanism to hide electroweak symmetry and give masses to the quarks and leptons?

(No EWSB agent at $v \approx 246$ GeV)

Consider effects of all SM interactions!
 $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

Without a Higgs Mechanism . . .

Electron and quarks would have no mass

QCD would confine quarks into protons, etc.
Nucleon mass little changed

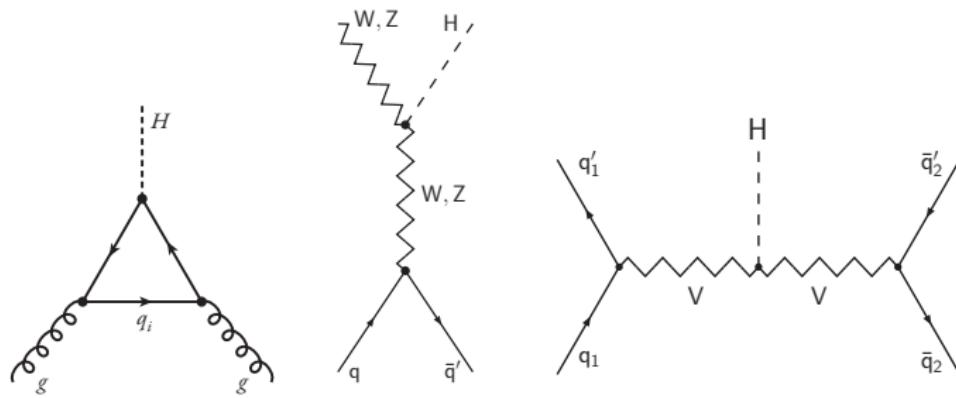
Surprise: QCD would hide EW symmetry,
give tiny masses to W, Z

Massless electron: atoms lose integrity

No atoms means no chemistry, no stable composite
structures like liquids, solids, . . .

LHC: Multiple looks at the new boson

3 production mechanisms, ≥ 5 decay modes



$\gamma\gamma, WW^*, ZZ^*, b\bar{b}, \tau^+\tau^-, Z\gamma(?)$

Questions for ATLAS and CMS

Fully accounts for EWSB (W, Z couplings)?

Couples to fermions?

Top from production, need direct observation for b, τ

Accounts for fermion masses?

Fermion couplings \propto masses?

Are there others?

Quantum numbers?

SM branching fractions to gauge bosons?

Decays to new particles? via new forces?

All production modes as expected?

Implications of $M_H \approx 126$ GeV?

Any sign of new strong dynamics?

Standard-model shortcomings

- No explanation of Higgs potential
- No prediction for M_H
- Doesn't predict fermion masses & mixings
- M_H unstable to quantum corrections
- No explanation of charge quantization
- Doesn't account for three generations
- Vacuum energy problem
- Beyond scope: dark matter, matter asymmetry, etc.

~ imagine more complete, predictive extensions

Beyond the Standard Model

More physics on the TeV scale?

Partial-wave unitarity analysis of WW scattering argues for new physics on the TeV scale.

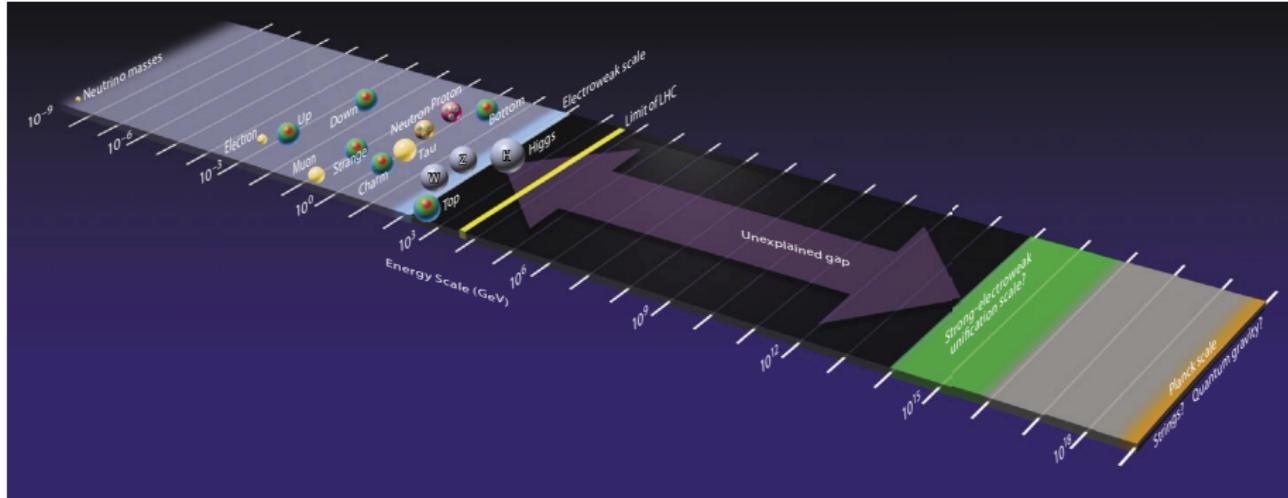
In SM: a Higgs boson or strongly interacting gauge sector

In general, something new on the TeV scale

At the level of suggestion, rather than theorem . . .

- The hierarchy problem: if light H , new physics implicated on the TeV scale
- WIMPs as dark matter: reproduce relic density for masses 0.1–1 TeV

The Hierarchy Problem



How to keep the distant scales from mixing in the face of quantum corrections? *OR*

How to stabilize the mass of the Higgs boson on the electroweak scale? *OR*

Why is the electroweak scale small?

The Hierarchy Problem

Possible paths

- Fine tuning
- A new symmetry (supersymmetry)
fermion, boson loops contribute with opposite sign
- Composite “Higgs boson” (technicolor . . .)
form factor damps integrand
- Little Higgs models, etc.
- Low-scale gravity (shortens range of integration)

All but first require new physics near the TeV scale

But Where is the New Physics?

The unreasonable effectiveness of the Standard Model

More Electroweak Questions for the LHC

- What is the agent that hides electroweak symmetry?
- Is the “Higgs boson” elementary or composite? How does the Higgs boson interact with itself? What triggers electroweak symmetry breaking?
- New physics in pattern of Higgs-boson decays?
- Will (unexpected or rare) decays of H reveal new kinds of matter?
- What would discovery of > 1 Higgs boson imply?
- What stabilizes M_H below 1 TeV?
- How can a light H coexist with absence of new phenomena?
- Is EWSB related to gravity via extra dimensions?

More Electroweak Questions for the LHC^{bis}

- Is EWSB emergent, connected with strong dynamics?
- If new strong dynamics, how can we diagnose? What takes place of H ?
- Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons?
- Does the different behavior of left-handed and right-handed fermions with respect to charged-current weak interactions reflect a fundamental asymmetry in the laws of nature?

More Electroweak Questions for the LHC^{ter}

- What will be the next symmetry recognized in Nature?
Is Nature supersymmetric? Is the electroweak theory part of some larger edifice?
- Are there additional generations of quarks and leptons?
- What resolves the vacuum energy problem?
- What lessons does electroweak symmetry breaking hold for unified theories of the strong, weak, and electromagnetic interactions?

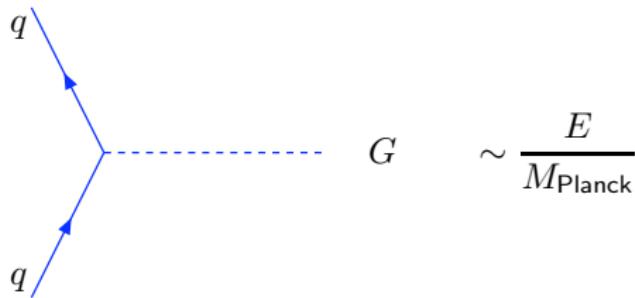
Thanks and good luck!

Why is empty space so nearly massless?

Natural to neglect gravity in particle physics . . .

Gravitational ep interaction $\approx 10^{-41} \times$ EM

$$G_{\text{Newton}} \text{ small} \iff M_{\text{Planck}} = \left(\frac{\hbar c}{G_{\text{Newton}}} \right)^{\frac{1}{2}} \approx 1.22 \times 10^{19} \text{ GeV large}$$



300 years after Newton: Why **is** gravity weak?

But gravity is not always negligible . . .

The vacuum energy problem

$$\text{Higgs potential } V(\varphi^\dagger \varphi) = \mu^2 (\varphi^\dagger \varphi) + |\lambda| (\varphi^\dagger \varphi)^2$$

At the minimum,

$$V(\langle \varphi^\dagger \varphi \rangle_0) = \frac{\mu^2 v^2}{4} = -\frac{|\lambda| v^4}{4} < 0.$$

Identify $M_H^2 = -2\mu^2$

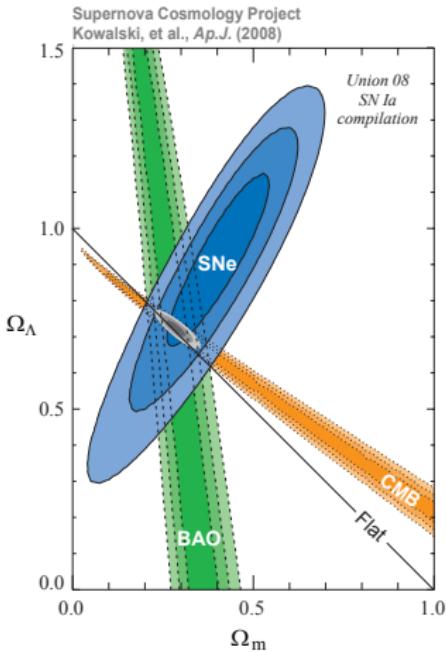
$V \neq 0$ contributes position-independent **vacuum energy density**

$$\varrho_H \equiv \frac{M_H^2 v^2}{8} \geq 10^8 \text{ GeV}^4 \quad \approx 10^{24} \text{ g cm}^{-3}$$

Adding vacuum energy density ϱ_{vac} \Leftrightarrow adding cosmological constant Λ to Einstein's equation

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu} \quad \Lambda = \frac{8\pi G_N}{c^4} \varrho_{\text{vac}}$$

Observed $\varrho_{\text{vac}} \lesssim 10^{-46} \text{ GeV}^4$



$\varrho_H \gtrsim 10^8 \text{ GeV}^4$: mismatch by 10^{54}

A chronic dull headache for thirty years ...